

Supersymmetry Studies

at a

Next - Generation

$e^+e^-$  Collider

M E Peskin  
"Circle Line Town"  
September 1999

my charge:

- Given
- the discovery of SUSY at Tevatron or LHC
  - the program of LHC measurements described by Hinchliffe yesterday

What new information will the  
Linear Collider bring?

Why is this question interesting?

- SUSY might be true
- SUSY is a "worked example" of physics beyond the Standard Model

do you really have to pay attention to the  
technical bits?

\* SUSY phenomenology is complex.

We need to know whether our proposed  
tools can penetrate this complexity.

and, please remember,

Theorists strive to build theories that are simple  
on the surface,  
but SUSY is about as well as they can do.

Nature strives only for underlying simplicity.

## Plan of this lecture

- Some basics of linear collider experimentation
- Bottom-up approach to the superspectrum (+ comparison to LHC)
- Theories of the superspectrum
- Snapshots of some variant phenomenologies

## "Linear Collider" (LC)

= an  $e^+e^-$  collider supplying  $\mathcal{L} \sim 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$   
at  $E_{cm} \sim 500 - 1500 \text{ GeV}$

major initiatives:

NLC            SLAC / LBL / LLL / Fermilab

JLC            KEK

TESLA        DESY

the required  $E_{cm}$  is set by the goals  
of the experimental program:

- Precision study of Higgs boson couplings  
to  $b, c, \tau, W, Z, g, \gamma$

$$E_{cm} \approx 150 \text{ GeV} + m_h$$

- Precision study of top quark couplings

$$E_{cm} \approx 400 \text{ GeV}$$

- Direct study of a strongly-coupled sector  
for electroweak symmetry breaking

$$E_{cm} \gtrsim 1500 \text{ GeV}$$

- Study of new particles from beyond the  
Standard Model

$$E_{cm} > 2m,$$

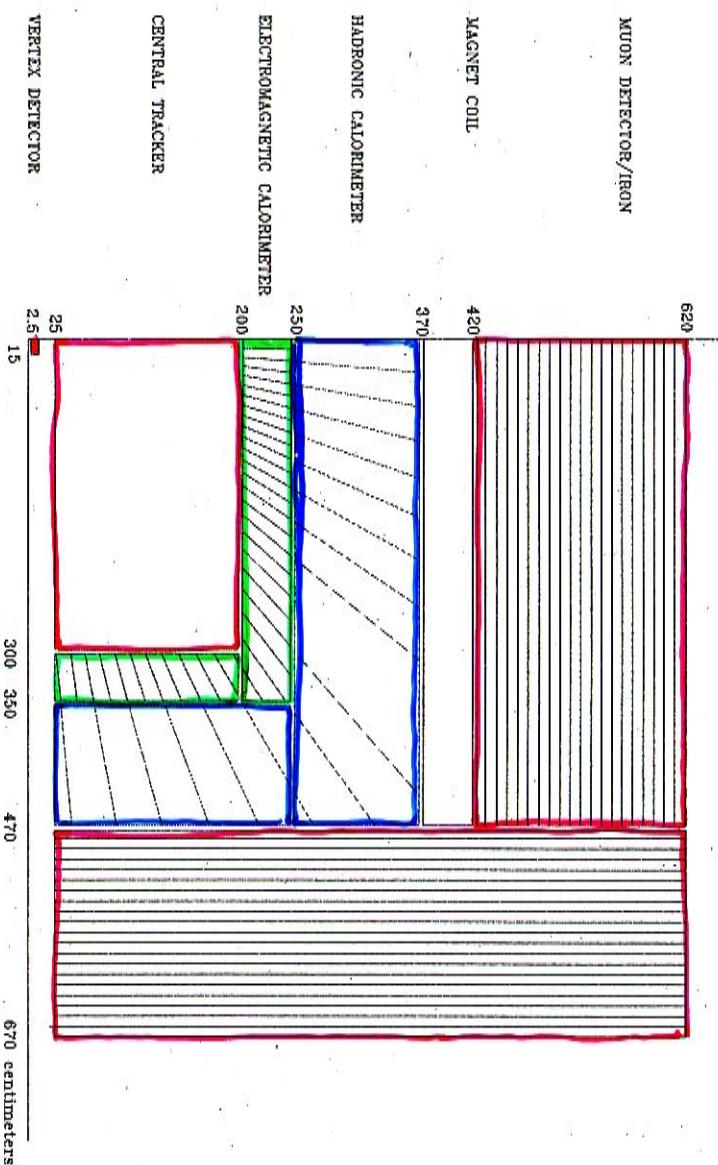
wherever they are found....

## Experimentation at a linear collider

- $100 \text{ fb}^{-1}/\text{yr} \rightarrow \underline{30,000 \text{ events/yr}}$  for  $\sigma = 1 \text{ R}$   
at  $E_{cm} = 500 \text{ GeV}$   
 $(\sim 100 \times \text{LEP 2 samples})$
- detector design issues similar to those for LEP2
- time structure:  
 $100 \text{ bunches/train} \times 100 \text{ trains/sec}$   
[spacing: 3 or 300 ns.]  
 $\rightsquigarrow$  no hardware trigger!
- machine backgrounds:
  - $\gamma\gamma \rightarrow \text{hadrons}$   $\sim 1/\text{train}$
  - $e^+e^-$  pairs
  - synchrotron rad.  $\gamma$ 's

## Sample detector:

DESIGN "L"  
QUADRANT VIEW  
(AS OF 10 DEC. 1998)



- CCD vertex detector, 1st layer within 1cm of interaction pt.
- TPC or silicon tracker
- High magnetic field: 3-6 T

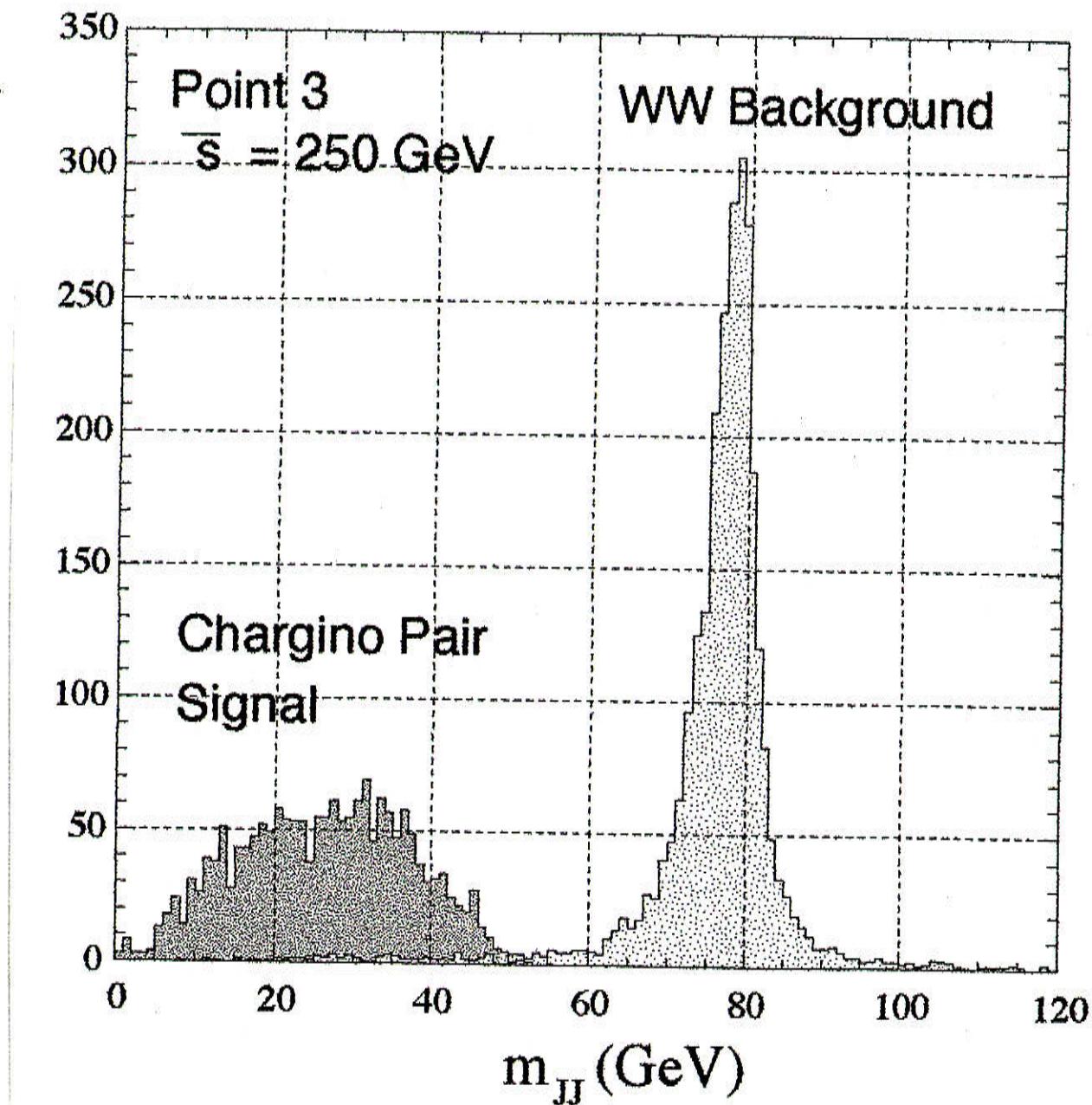
for more info:  
<http://www-sldnt.slac.stanford.edu/nrd/>

## Issues of special interest for SUSY:

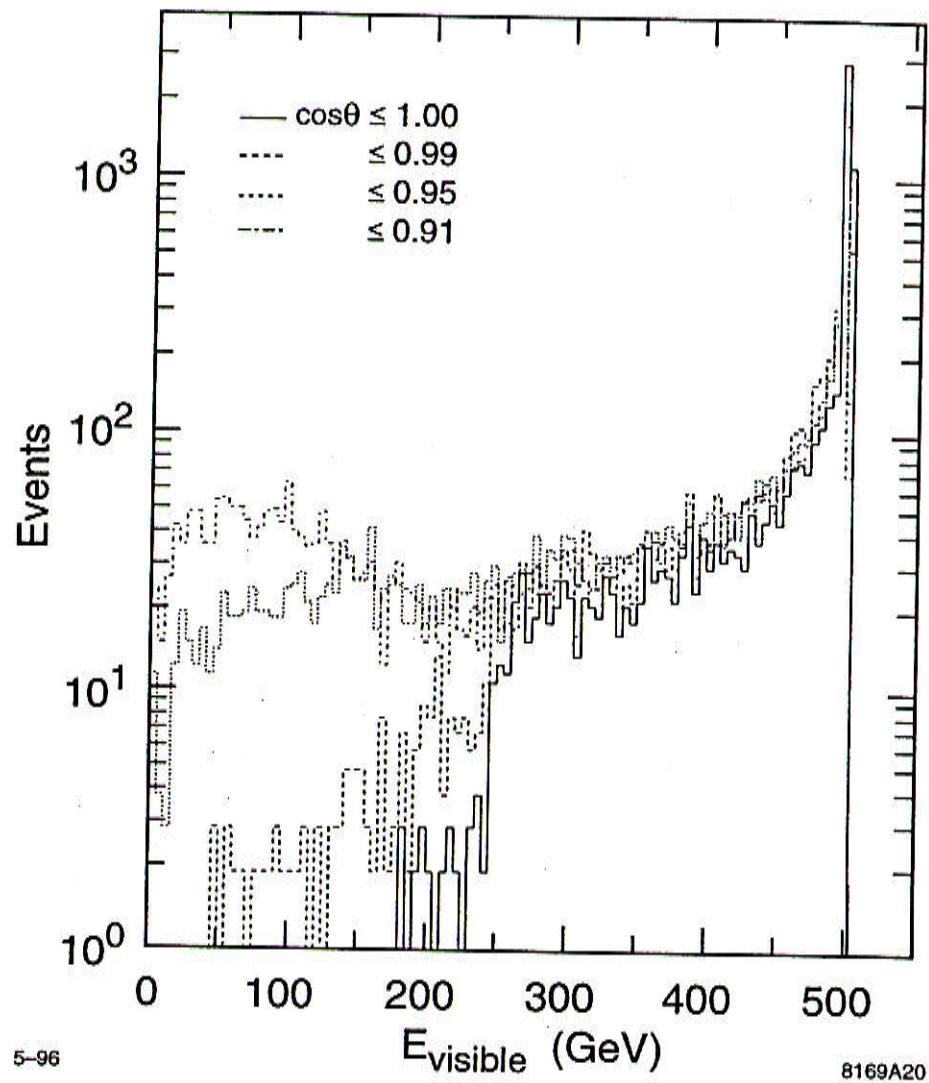
- $q\bar{q}$  mass distributions can be used without exotic selection cuts  
calorimetrically separate  $W/Z/\chi$
- hermiticity : sensitivity down to  
100 mrad.  $(\cos \Theta = 0.995)$

Snowmass '96

$m(jj)$  in  $e^+e^- \rightarrow l\nu jj$



N2C report to  
Snowmass '96



- $\frac{d\hat{\mathcal{L}}}{d\hat{s}}$

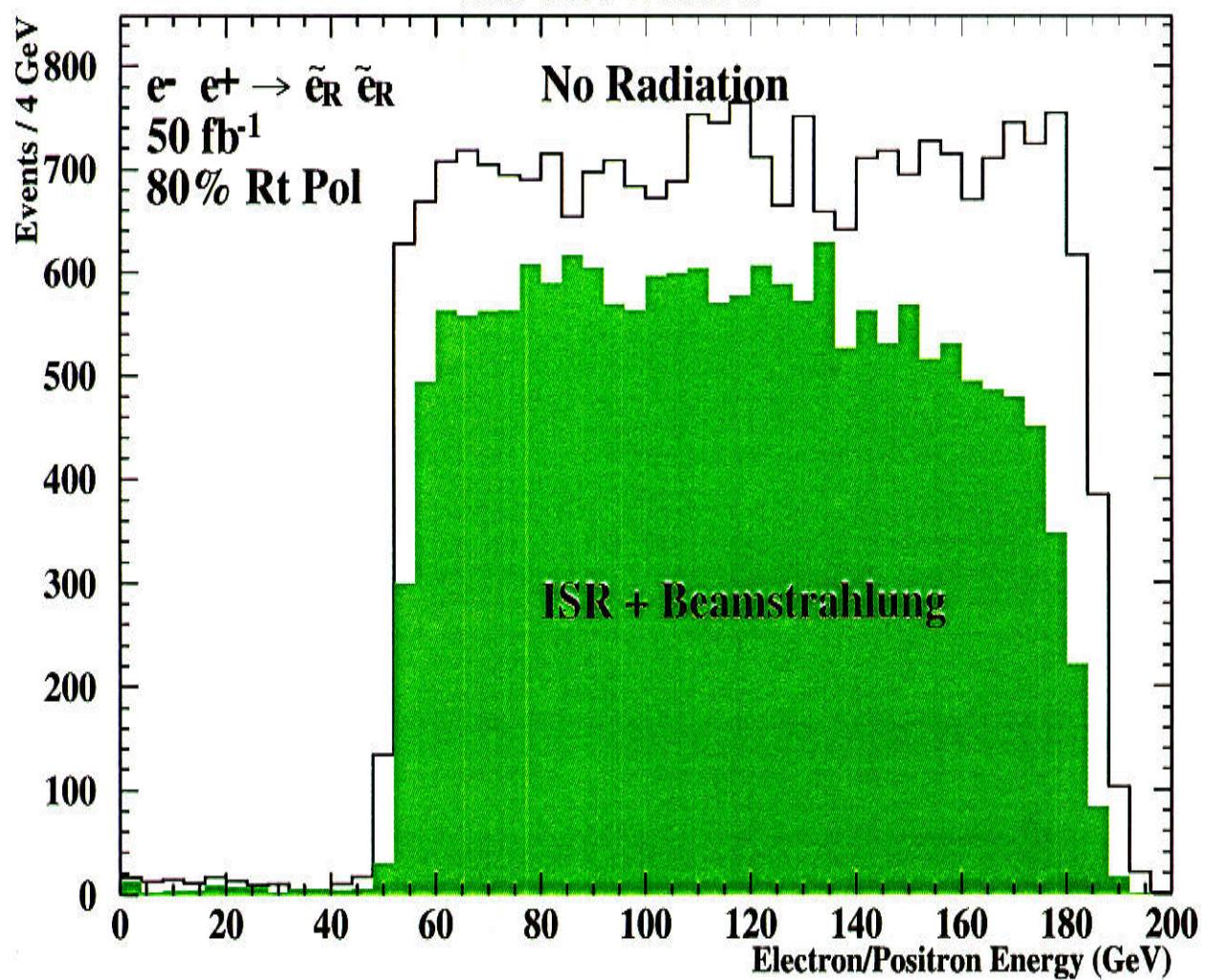
Initial State Radiation + beamstrahlung  
cause a  $\sim 10\%$  loss from  
nominal to effective  $E_{cm}$

Measure the spectrum using acollinear  
Bhabhas detected in endcaps  
(rate  $\sim 100 R$ )

treat as a higher-order correction  
in physics analyses

The spectrum is sharply peaked at  $x=1$ ,  
so it does not affect the positions of  
thresholds in  $\sqrt{s}$ .

### 500 GeV Point 3



- polarization :

$e^-$  polarization allows us to tune  
the size of signals and/or backgrounds

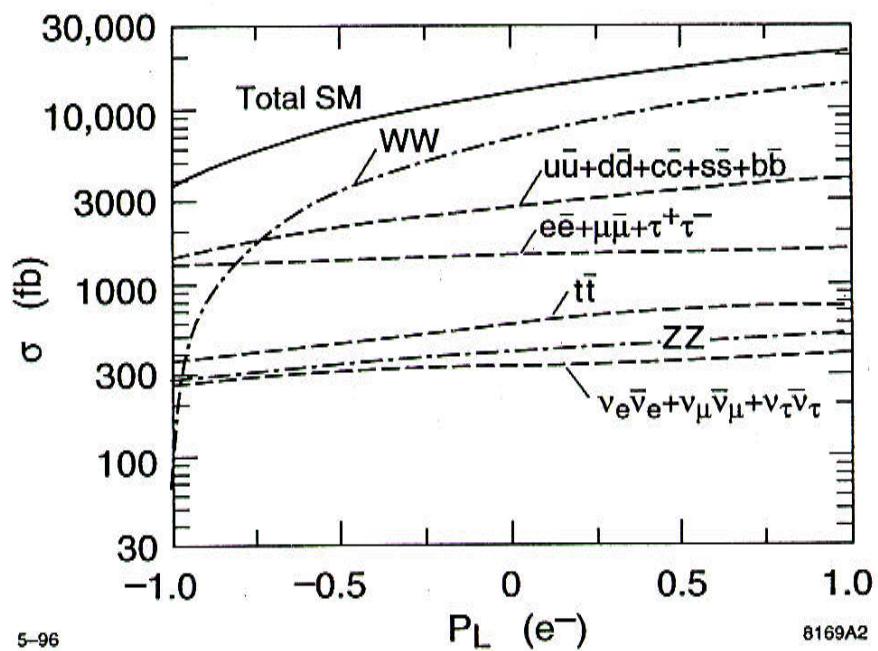
$e^+e^- \rightarrow W^+W^-$  is often the major  
background to SUSY analyses,

$$\text{but } \sigma(e_R^-) / \sigma(e_L^-) = 1/30$$

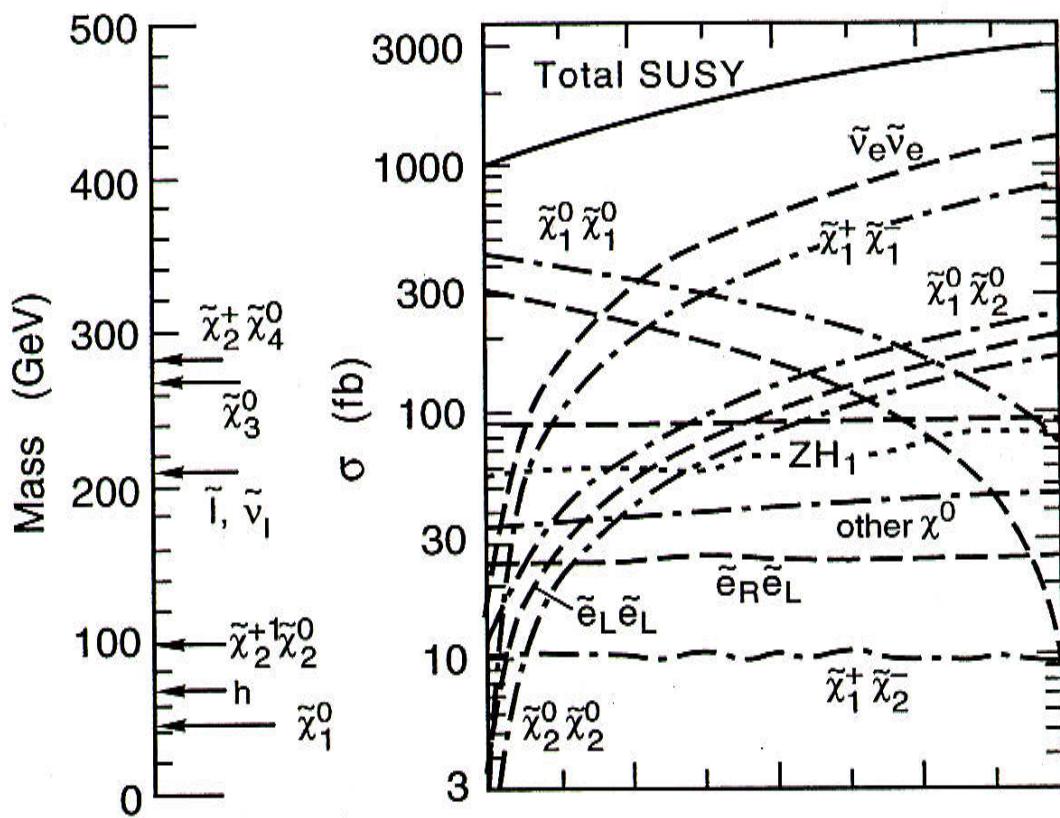
the SLC now has 80%  $e^-$  pol;  
we hope for 90% for NLC

TESLA proposes also 60%  $e^+$  polarization

## Standard Model processes



## SUSY processes



- adjustable  $E_{cm}$

the complexity of SUSY production processes  
can be simplified by working from the  
bottom of the spectrum up

the best experimental strategy will be  
a flow chart.

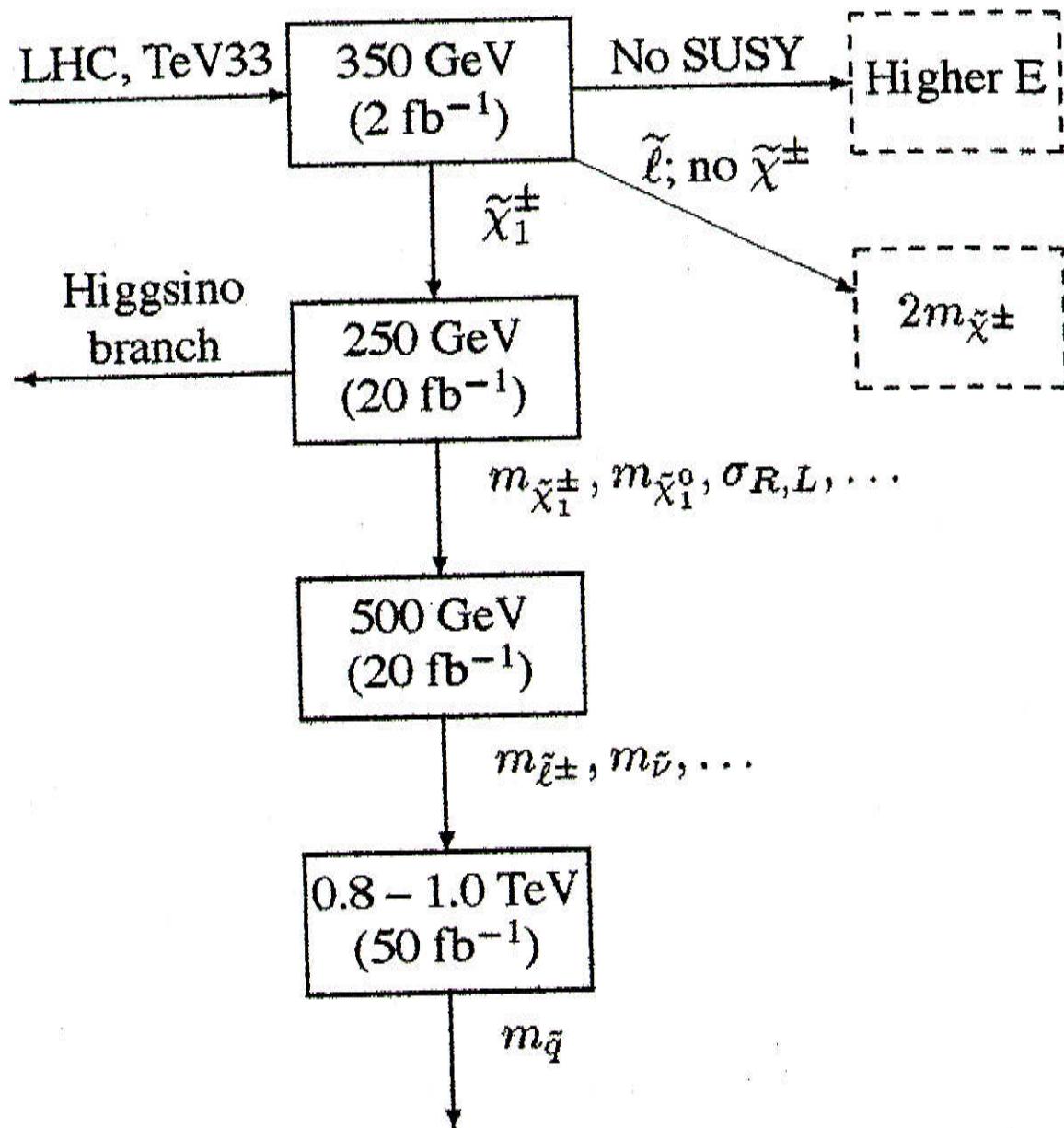
S<sub>L</sub> budget :

$20 \text{ fb}^{-1}$  for kinematic mass measurements

$100 \text{ fb}^{-1}$  for  $d\sigma/d\cos\theta$ , mixing angle  
measurements

$100 \text{ fb}^{-1}$  for precision location of  
thresholds.

Showmass '96 point 3  
strategy



now analyze specific SUSY processes  
that may appear in  $e^+e^-$  annihilation

in this segment, I consider only

- R-parity conserving scenarios  
with missing-energy signatures
- the lightest particle in the SUSY  
spectrum  
 $(\tilde{l}^-, \tilde{\chi}^0, \tilde{\chi}^+, \tilde{t})$

this said, we can discuss each process  
without need for detailed model of the  
superspectrum



Bottom-up a cumulative approach  
to superspectroscopy

$$e^+ e^- \rightarrow \tilde{\ell}^- \tilde{\ell}^+$$

easiest case:  $e^+ e^- \rightarrow \tilde{\mu}_R^- \tilde{\mu}_R^+ , \tilde{\mu}_R^- \rightarrow \mu^- \tilde{\chi}^0$

$$\frac{d\sigma}{d\cos\theta}(e_R^- e^+) = \frac{\pi\alpha^2}{4S} \beta^3 \sin^2\Theta$$

$$\cdot \left\{ \left| 1 + \frac{s_W^2}{c_W^2} \frac{s}{s-m_Z^2} \right|^2 + \left| 1 - \frac{s_W^2}{c_W^2} \frac{s}{s-m_Z^2} \right|^2 \right\}$$

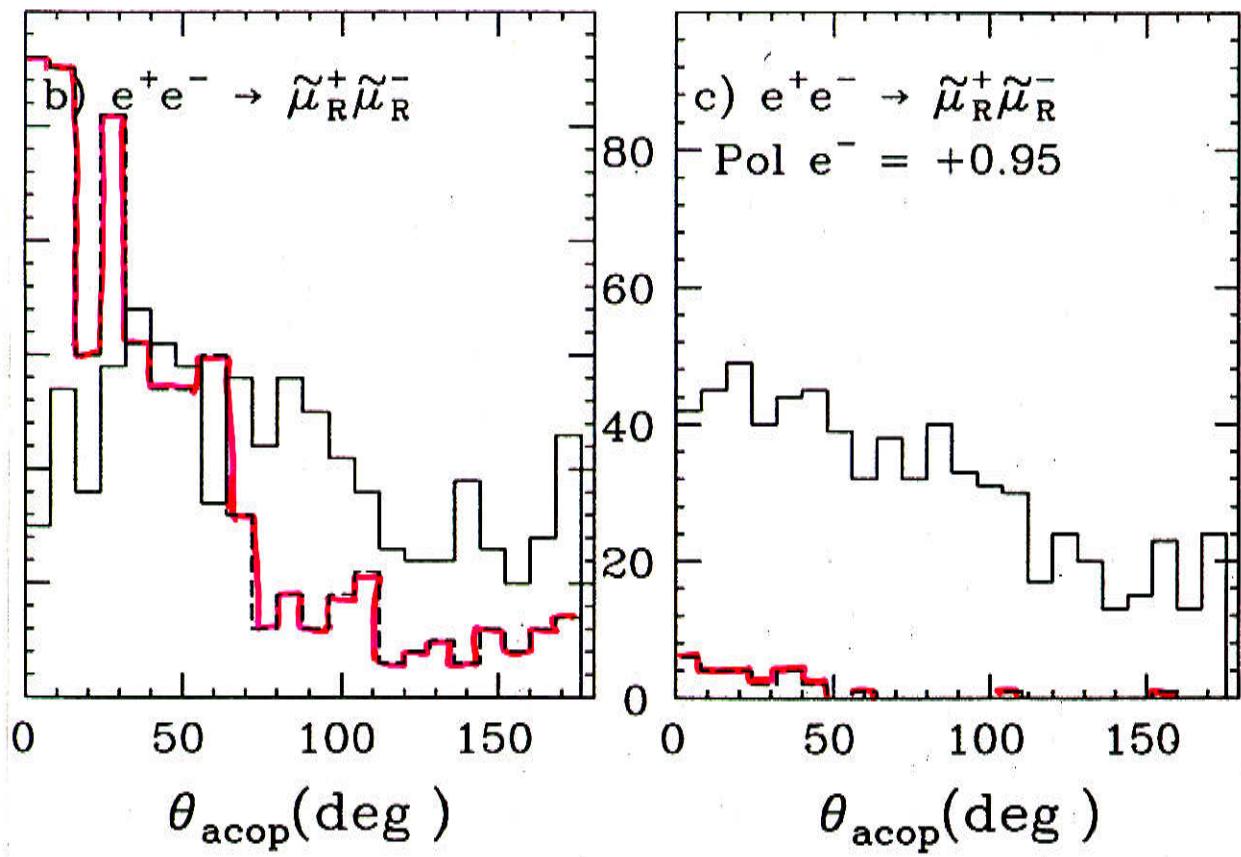
event selection: acoplanar  $\mu$  pairs

major background:  $e^+ e^- \rightarrow W^+ W^- \rightarrow \mu^+ \nu \mu^- \bar{\nu}$   
 (use  $e^-$  polarization)

The total cross section depends only on

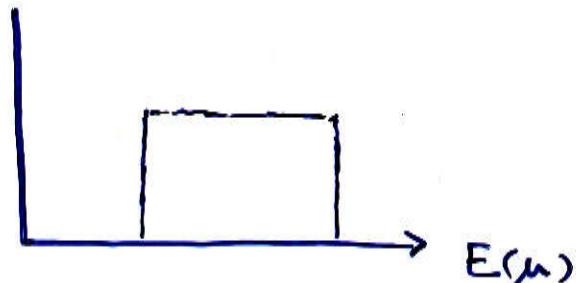
spin  $\Theta$  + St. Model Qu. Nos.

Tsukamoto et al



$\tilde{\mu}$  mass measurement:

Tsukamoto et al.: isotropic decay + fixed boost  
 $\Rightarrow$  flat distribution of  $E(\mu)$

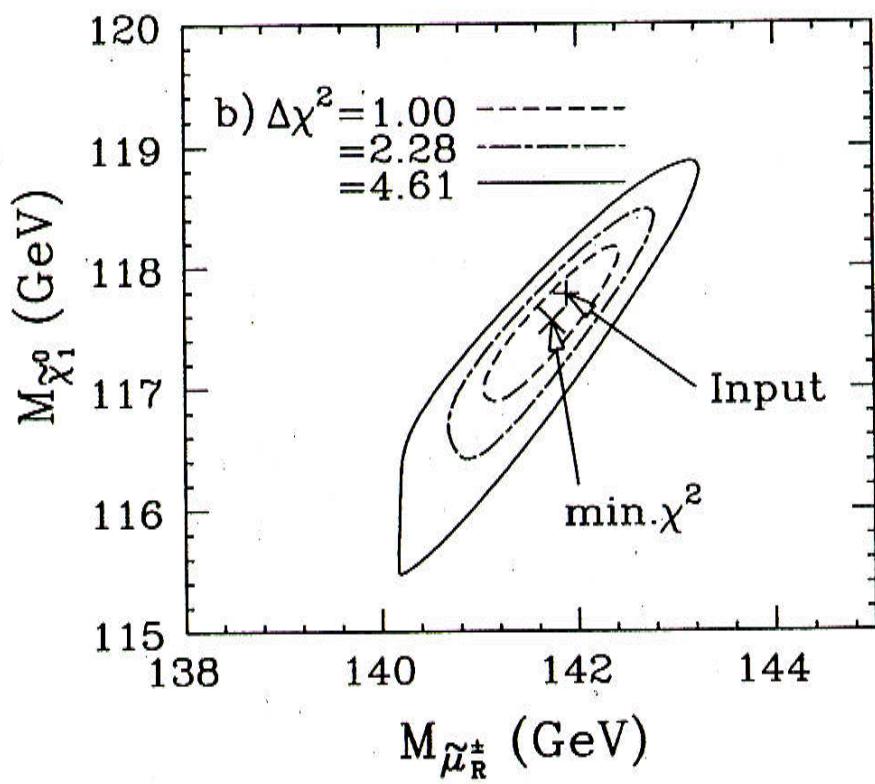
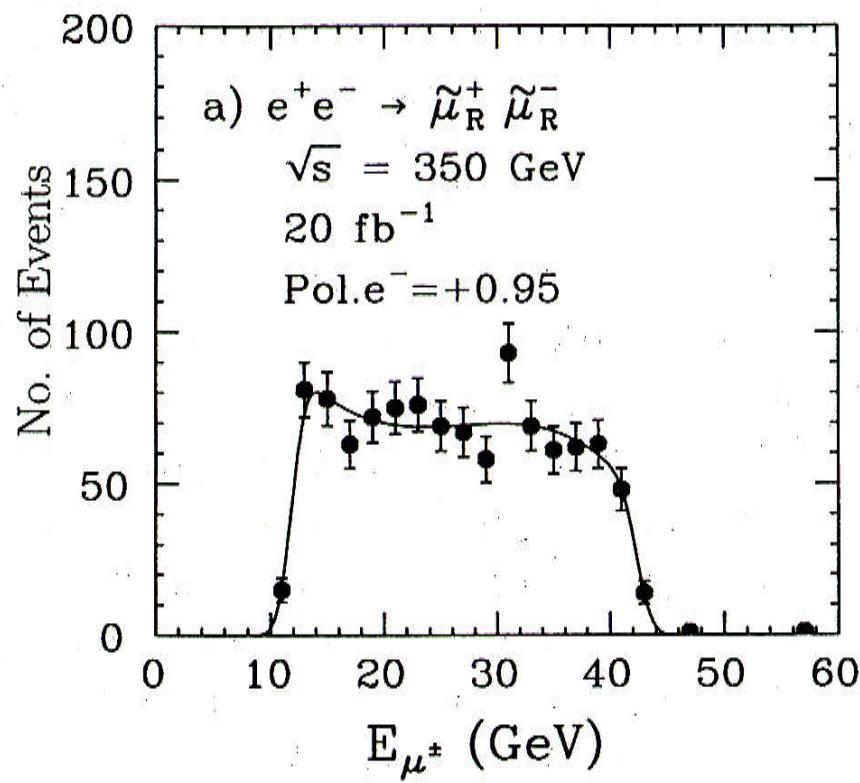


endpoints at  $E/E_{beam} = \frac{1}{2}(1 \pm \beta)(1 - \frac{m_{\chi^0}^2}{m_{\tilde{\mu}}^2})$

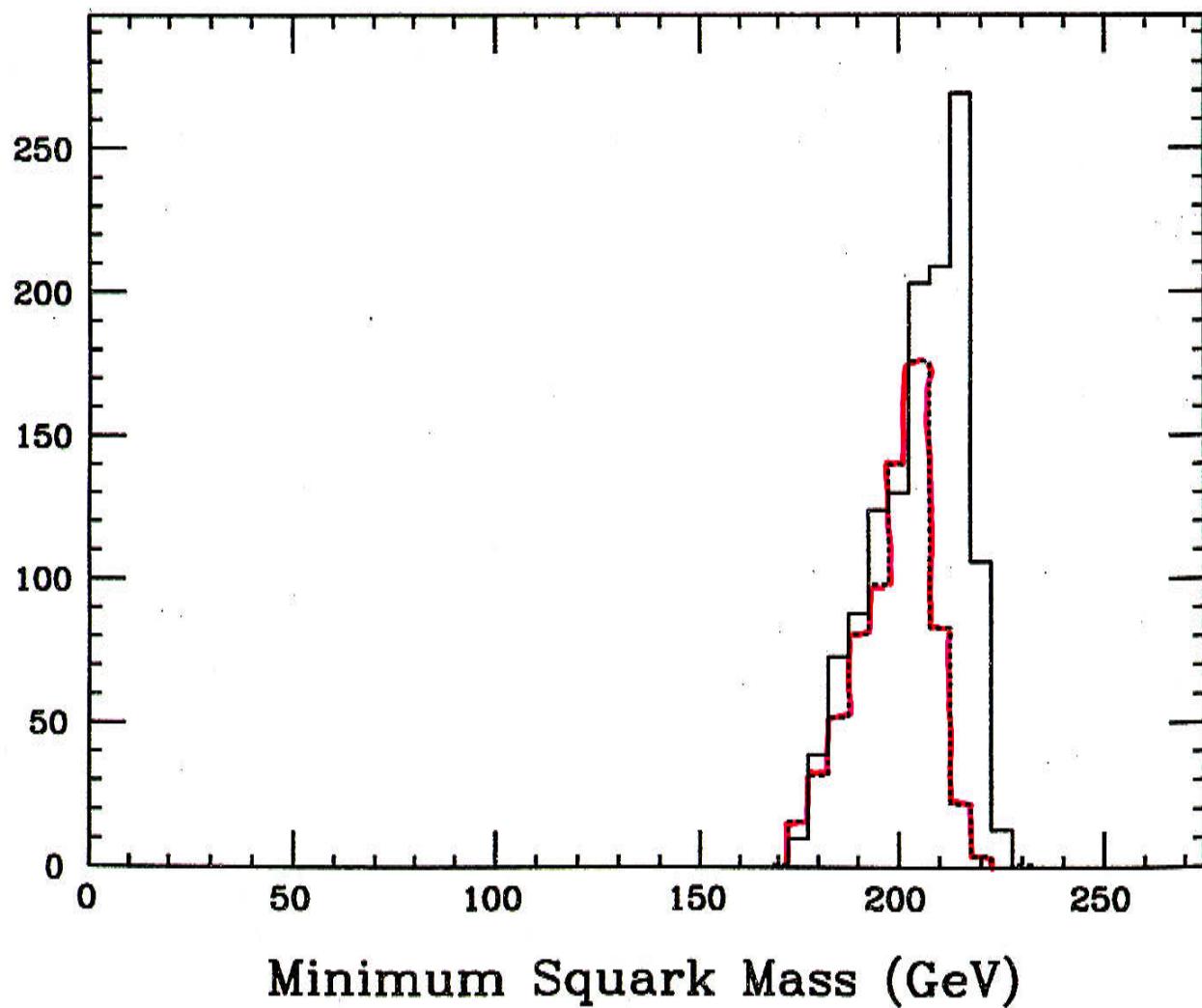
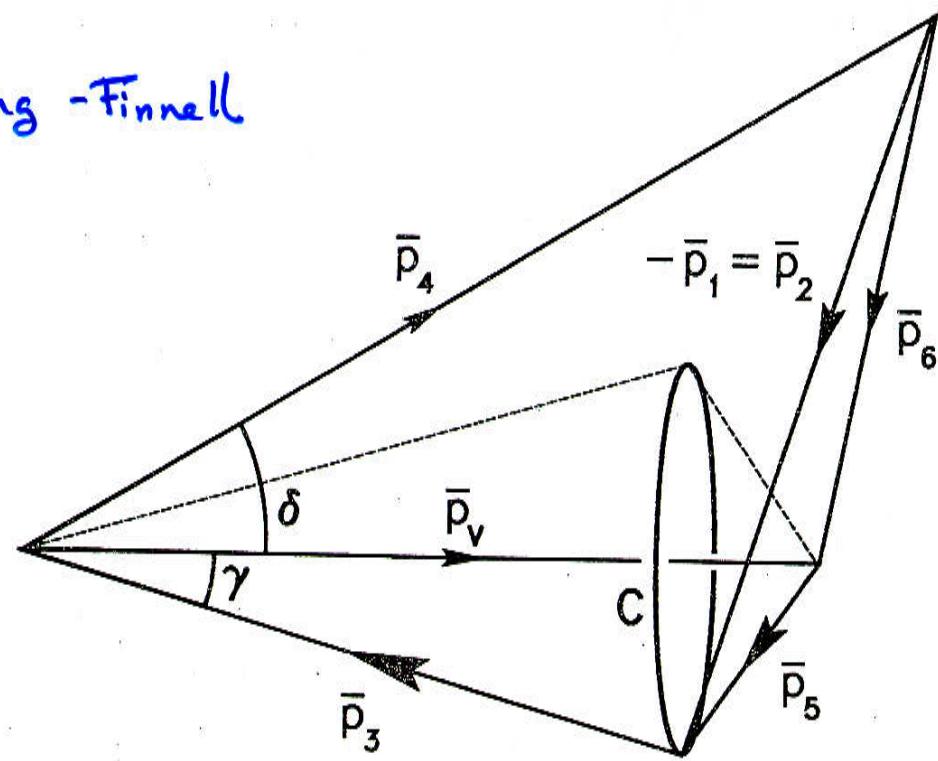
endpoint locations  $\rightarrow m(\tilde{\mu}), m(\tilde{\chi}^0)$

w. accuracy  $\sim 1\%$

Feng Finnell:  
given  $\mu^+\mu^-$  vectors, compute the  
minimum  $m(\tilde{\mu})$  allowed by kinematics  
Typically, this peaks sharply at the  
true  $m(\tilde{\mu})$ .



Feng - Finnell



since  $\tilde{\mu}_L$  and  $\tilde{\mu}_R$  are distinct species,  
they have distinct superpartners

often  $m(\tilde{\mu}_L) / m(\tilde{\mu}_R) \sim 1.5 - 2$

as long as both have substantial branching  
ratio to  $\mu^- \tilde{\chi}_1^0$ , we can use the  
endpoint technique to find both masses

This technique applies more generally  
to any process

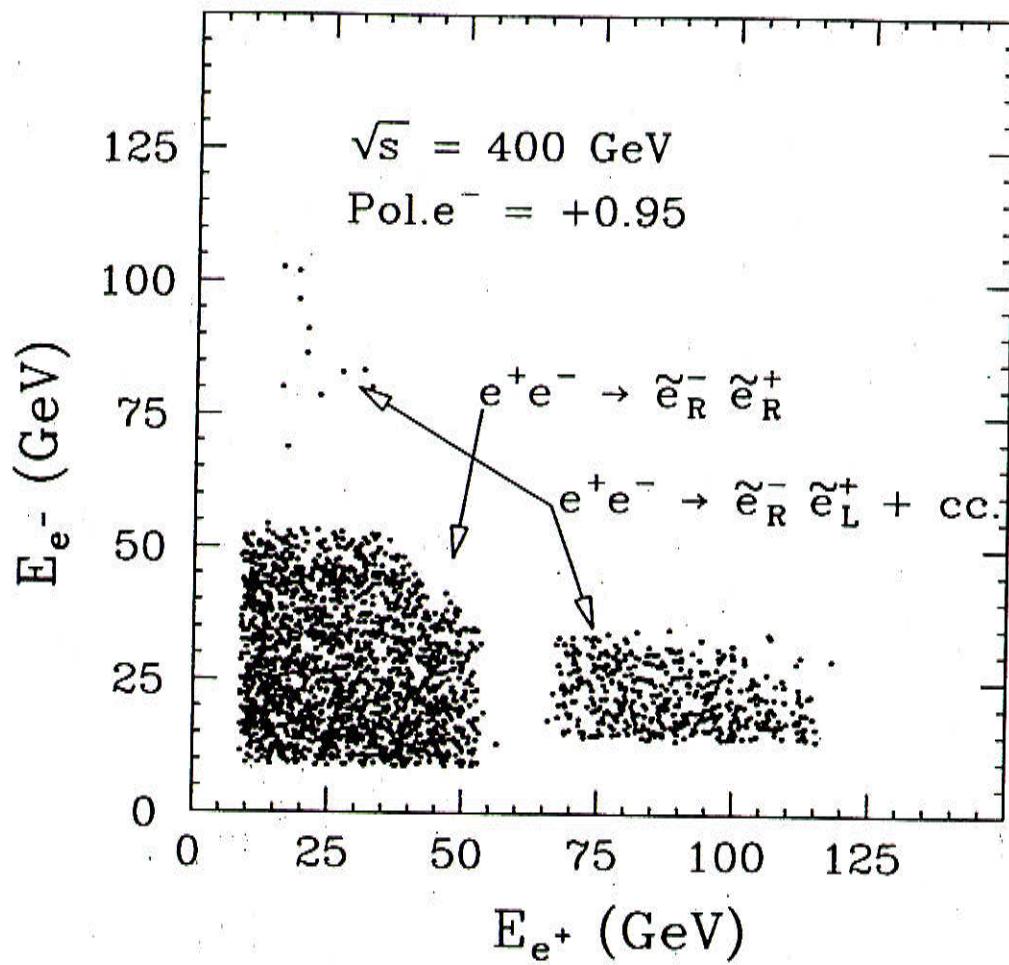
$$e^+ e^- \rightarrow S \bar{S} \quad S \rightarrow 2\text{body}$$

e.g. comparison of endpoints in  $E(\text{jet})$   
for  $e_L^- e^+ \rightarrow \tilde{q}_L \tilde{g}$ ;  $e_R^- e^+ \rightarrow \tilde{q}_R \tilde{g}$

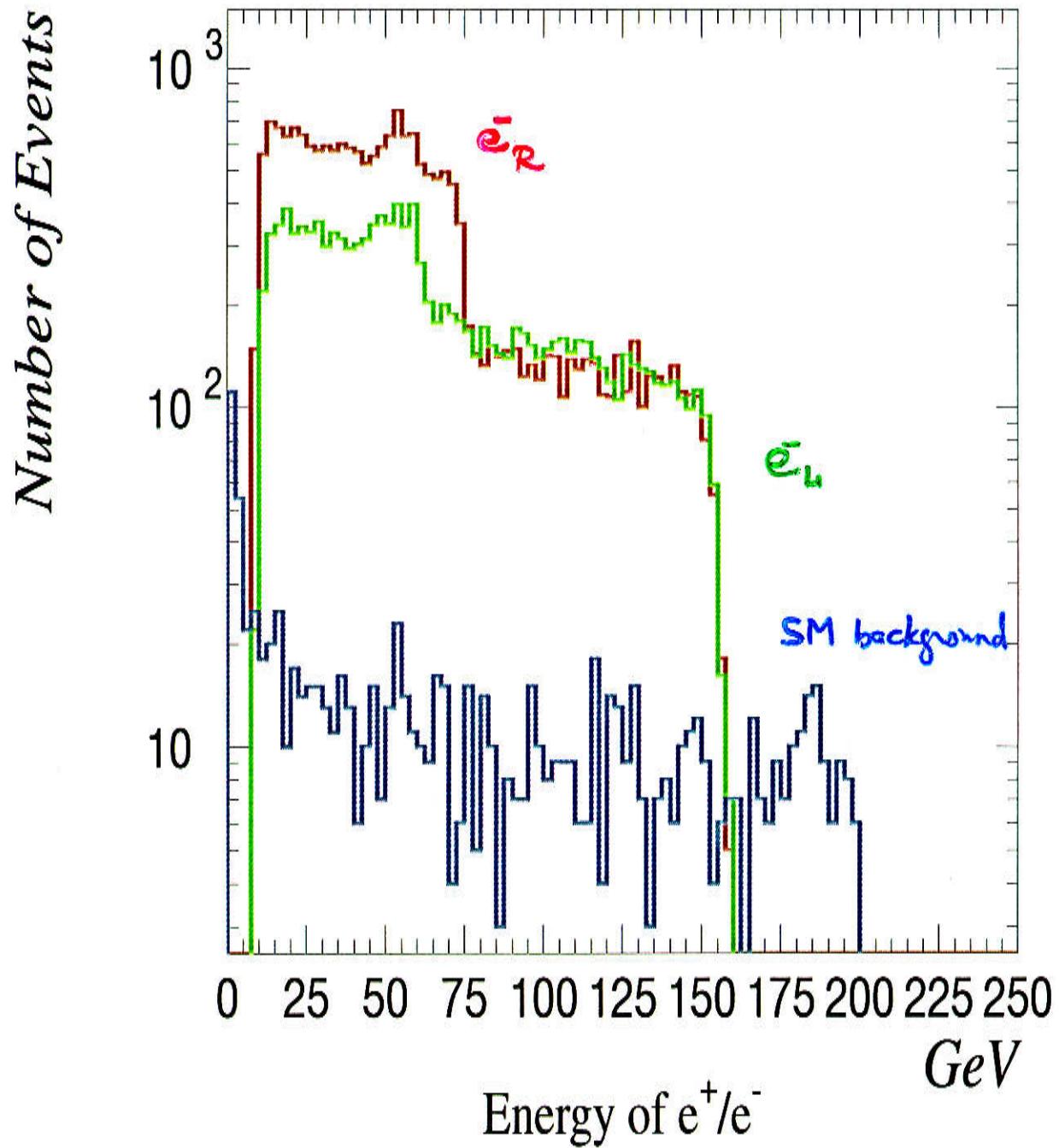
allows a 1% measurement of

$$m(\tilde{q}_L) - m(\tilde{q}_R)$$

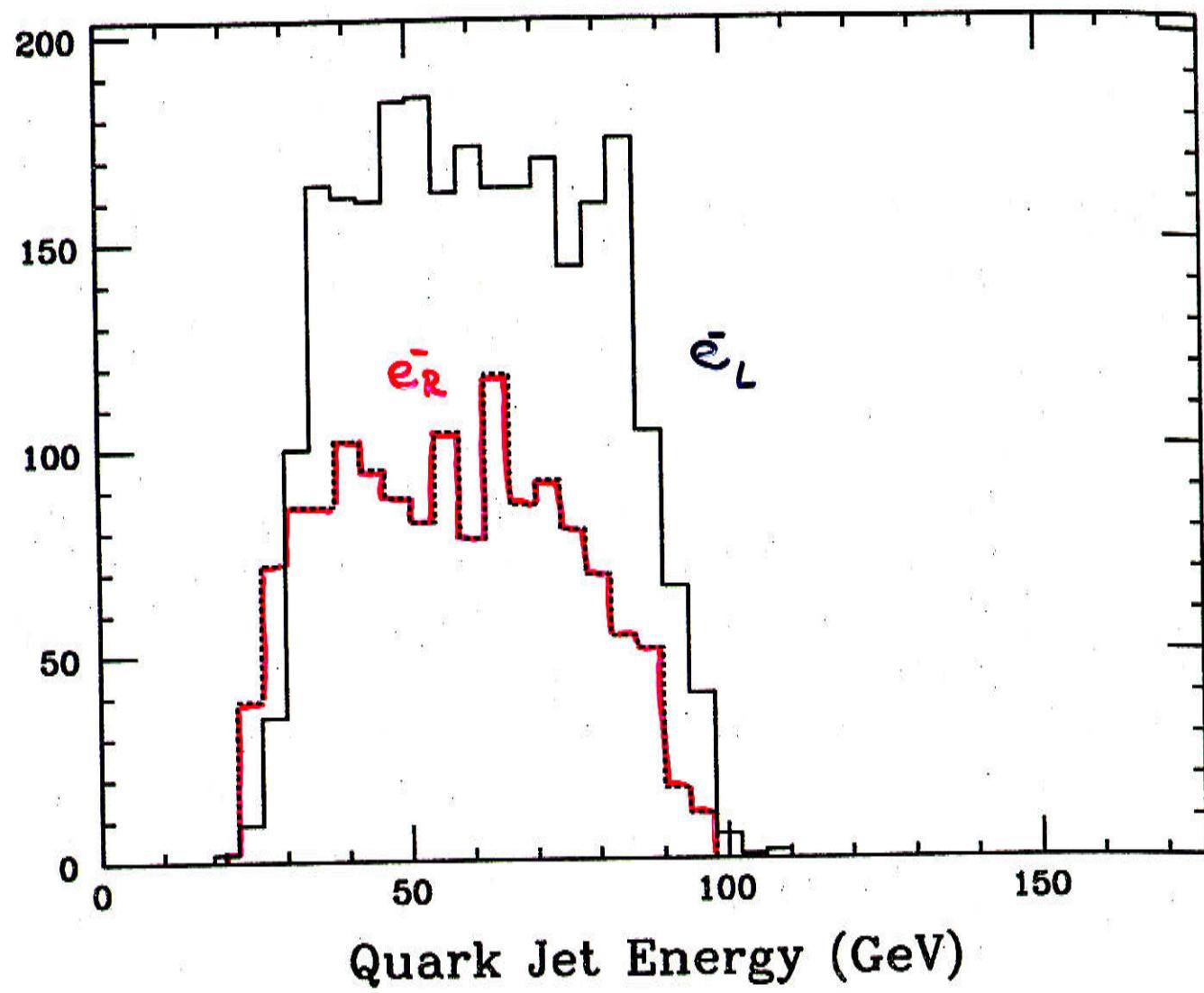
Tsukamoto  
et al.



Goodman et al.



Feng-Finnell

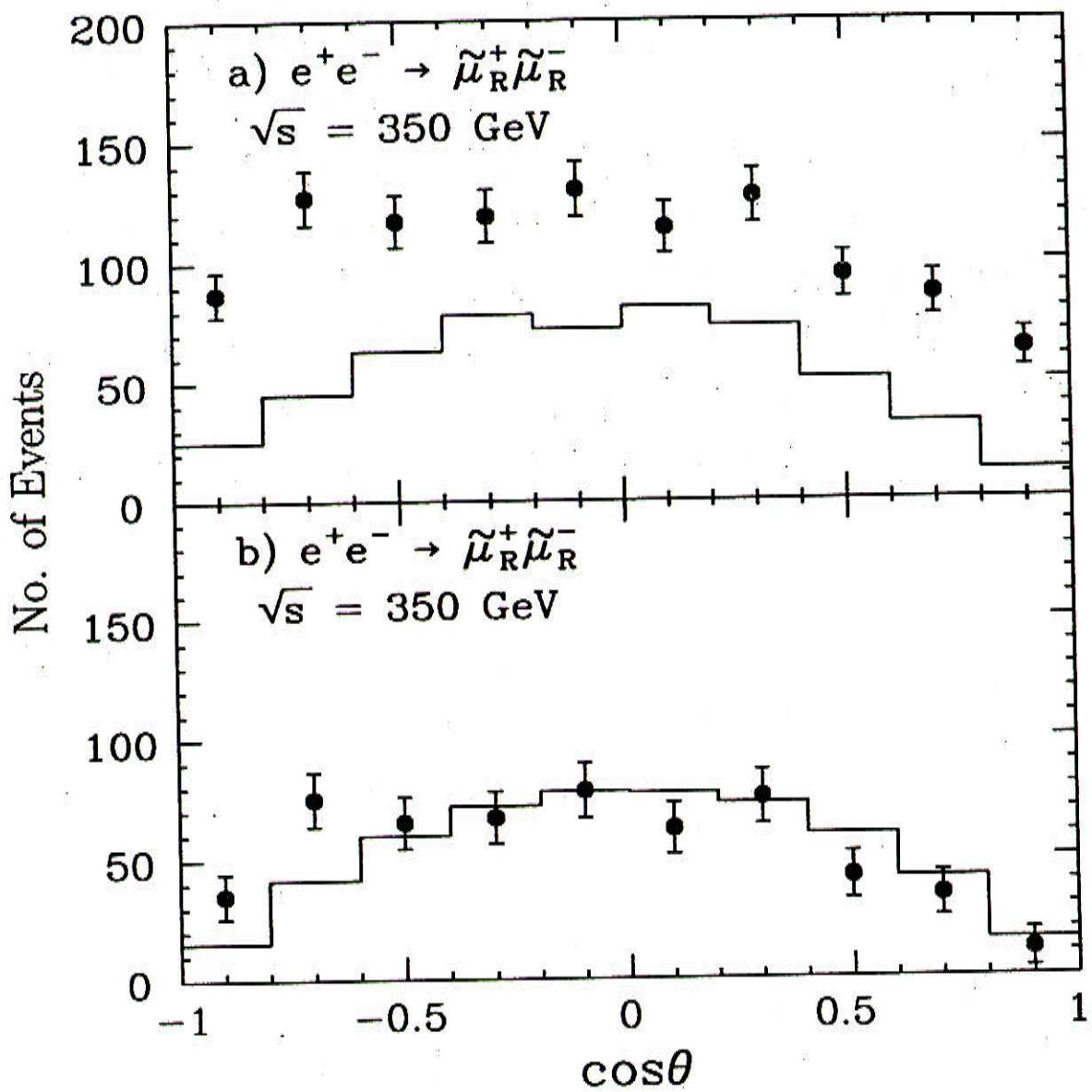


angular distributions:

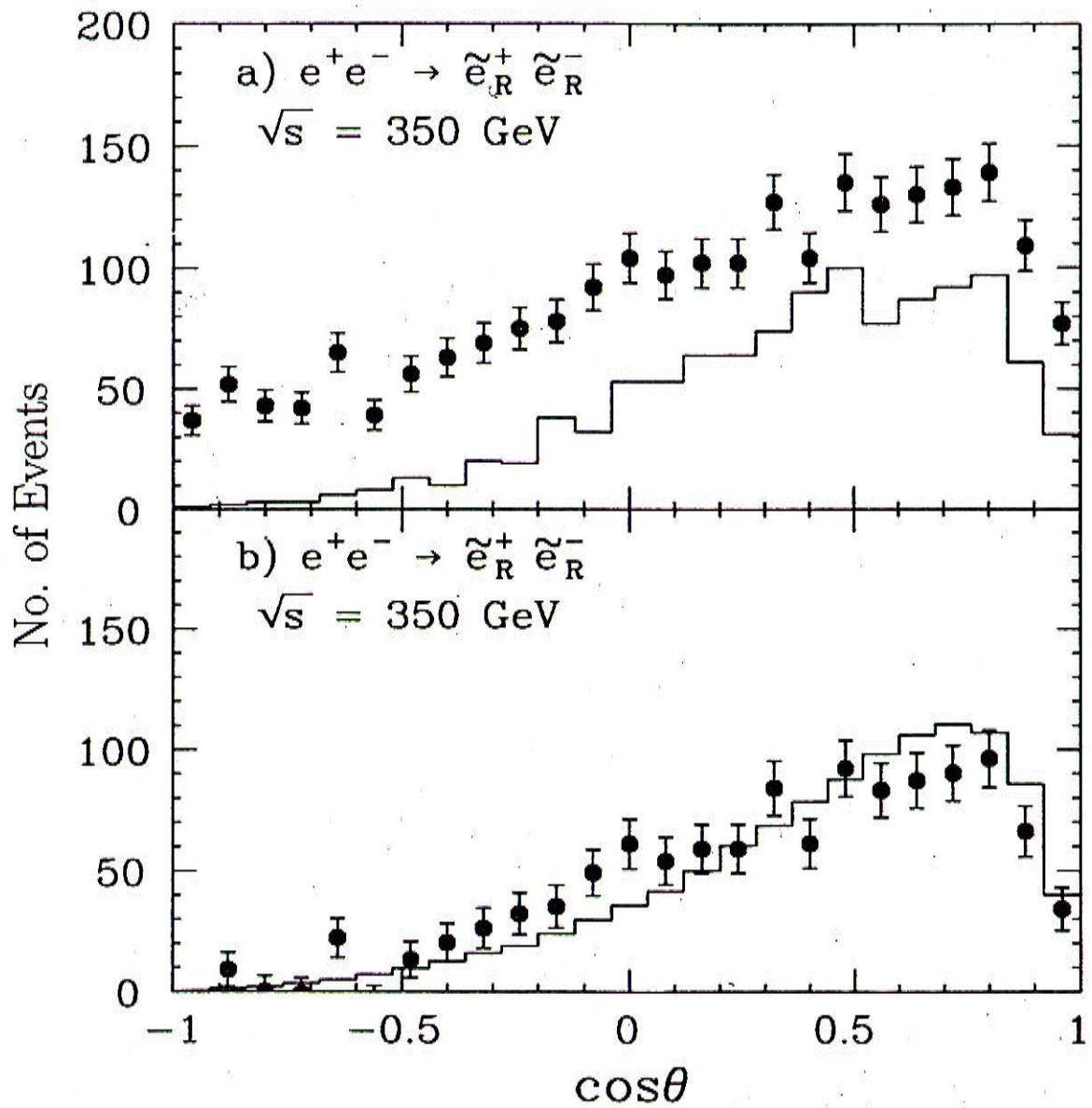
given  $\mu^+ \mu^-$  vector and  $m(\hat{\mu}^+), m(\hat{\chi}^0)$ ,  
there are 2 solutions for  $\cos \Theta$

the wrong solutions give a flat background  
that may be subtracted to  
determine  $d\sigma/d\cos \Theta$

Tsukamoto et al

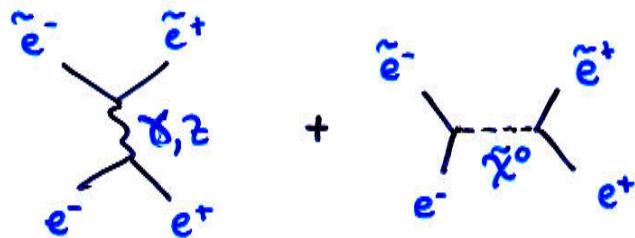


Tsukamoto et al



Studying  $e^+e^- \rightarrow \tilde{e}^+\tilde{e}^-$

brings in t-channel  $\tilde{\chi}^0$  exchange



$$\frac{d\sigma}{d\cos\theta} (e_R^- e_L^+ \rightarrow \tilde{e}_R^- \tilde{e}_L^+)$$

$$= \frac{\pi \alpha}{2s} \beta^3 \sin^2 \Theta \left| \frac{s}{M_1^2} N_{RR}(t) - \left( 1 + \frac{s_W^2}{c_W^2} \frac{s}{s-m_1^2} \right) \right|^2$$

typically, the t-channel diagram dominates,  
allowing measurement of the couplings to the  
neutralino sector

Chargino mixing:  $(\tilde{\omega}^+, \tilde{h}^+) \rightarrow \tilde{\chi}_i^+$

$$\Delta \mathcal{L} = - (\tilde{\omega}^- \tilde{h}^-)^T c \tilde{m} (\begin{matrix} \tilde{\omega}^+ \\ \tilde{h}^+ \end{matrix})$$

$$\tilde{m} = \begin{pmatrix} m_2 & \sqrt{2}m_W \cos\beta \\ \sqrt{2}m_W \cos\beta & \mu \end{pmatrix} = V M V^T$$

neutralino mixing:  $(\tilde{b}, \tilde{\omega}^0, \tilde{h}_1^0, \tilde{h}_2^0) \rightarrow \tilde{\chi}_i^0$

$$\tilde{m} = V M V^T$$

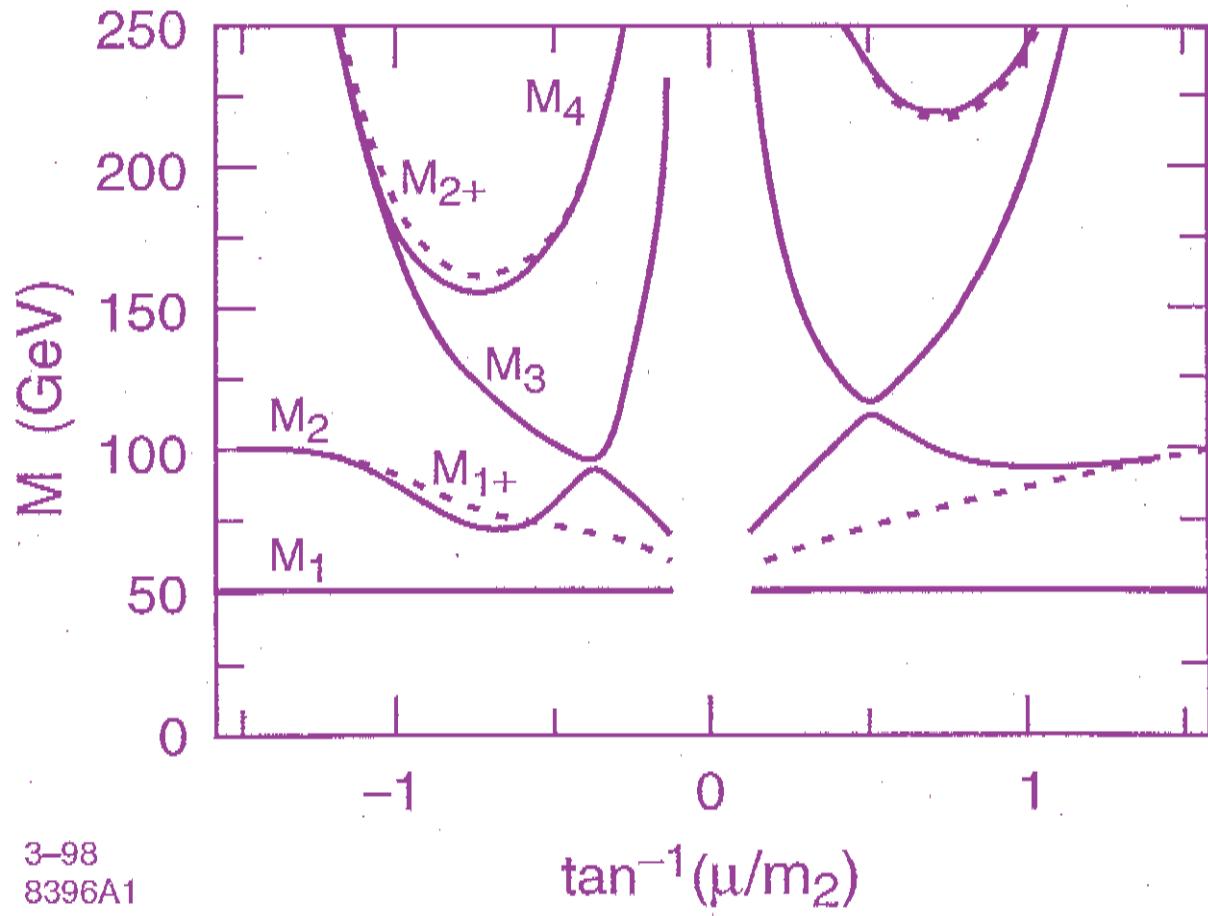
"gaugino region":  $|\mu| \gg m_2 \gg m_W$

"Higgsino region":  $m_2 \gg |\mu| \gg m_W$

all 6 LHCC SUGRA points are in the  
gaugino region

$$m(\chi_1^+) \approx m(\chi_2^0) > m(\tilde{\chi}_1^0)$$

a consequence of SUGRA constraints  
+ electroweak symmetry breaking



3-98  
8396A1

neutralino functions :

$$N_{ab}(t) = \sum_i V_{ai} \frac{M_i^2}{M_i^2 - t} V_{bi}^*$$

$$V_{Ri} = \frac{1}{c_W} V_{1i} \quad V_{Li} = \frac{1}{2c_W} V_{1i} + \frac{1}{2s_W} V_{2i}$$

in the gaugino limit :

$$N_{RR}(0) \rightarrow \frac{1}{c_W} \quad N_{LL}(0) \rightarrow \frac{1}{4c_W^2} + \frac{1}{4s_W^2} \frac{m_1^2}{m_2^2}$$

then

$$\bar{e}_R^- e_L^+ \rightarrow \tilde{e}_R^- \tilde{e}_R^+ \quad \text{probes} \quad N_{RR}(t)$$

$\rightsquigarrow$  test of gaugino/Higgsino nature of  $\tilde{\chi}_1^0$

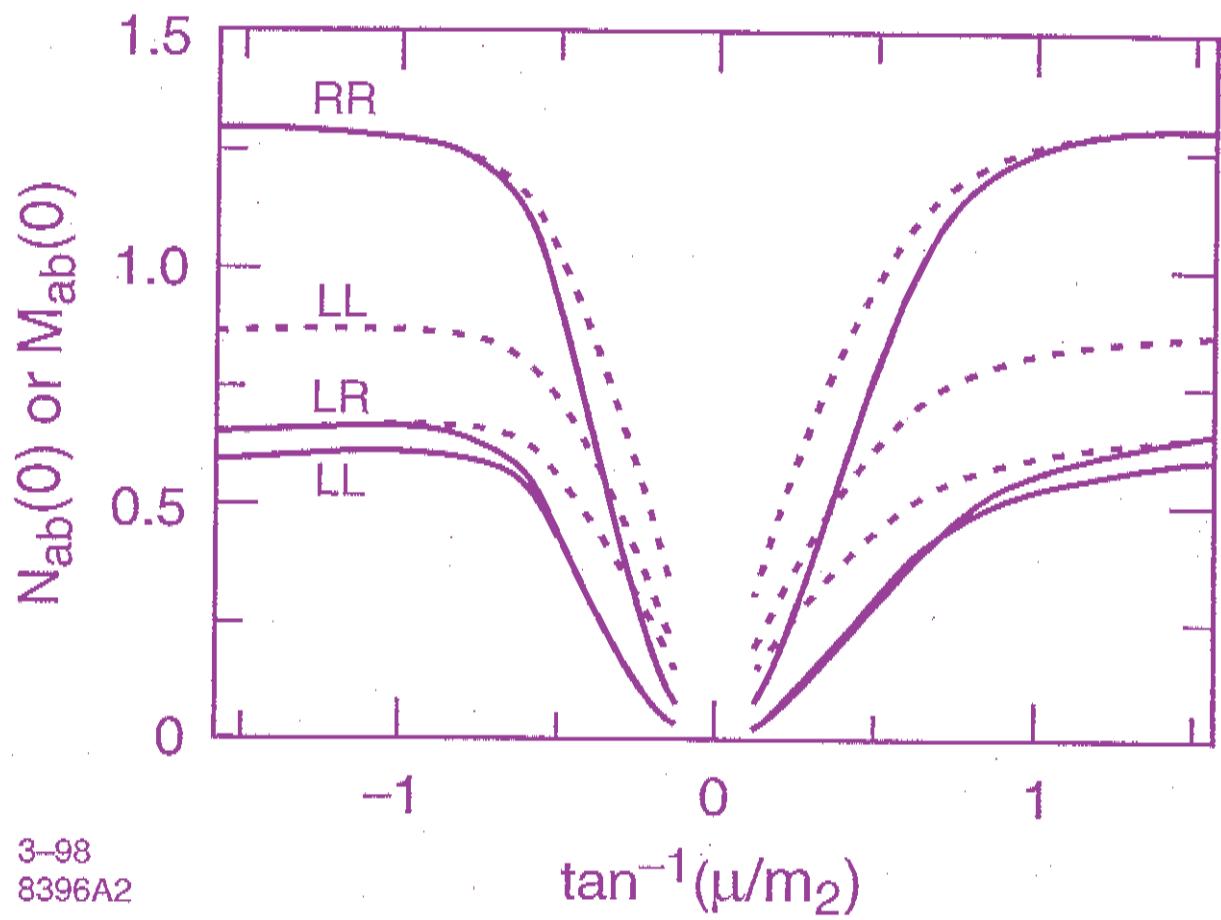
$$\bar{e}_L^- e_R^+ \rightarrow \tilde{e}_L^- \tilde{e}_L^+ \quad \text{probes} \quad N_{LL}(t)$$

$\rightsquigarrow$  measurement of  $m_1/m_2$

in addition

$$\bar{e}_R^- \bar{e}_R^- \rightarrow \tilde{e}_R^- \tilde{e}_R^- \quad \text{probes} \quad M_{RR}(t)$$

$$\bar{e}_L^- \bar{e}_L^- \rightarrow \tilde{e}_L^- \tilde{e}_L^- \quad \text{probes} \quad M_{LL}(t)$$



3-98  
8396A2

If there is evidence from other sources (e.g.  $\tilde{\chi}$  masses) that we are in the gauginos region, we can use  $\tilde{\chi}$  exchange to test the SUSY relation of couplings e.g.:  $\frac{g_{e\tilde{e}\tilde{b}}}{\sqrt{2}g'} = \frac{g_{e\tilde{e}\tilde{b}}}{\sqrt{2}g'}$

Nojiri Fujii Tsukamoto

Nojiri Pierce Yamada

Cheng Feng Polonsky

Katz Randall Su

$$\frac{g_{e\tilde{e}\tilde{b}}}{\sqrt{2}g'} = 1 \pm 1\% \text{ from } \tilde{e}_R^-\tilde{e}_R^+ \\ \pm 0.3\% \text{ from } \tilde{e}_R^-\tilde{e}_R^-$$

$100 \text{ fb}^{-1}$

$$\frac{g_{e\tilde{e}\tilde{b}}}{\sqrt{2}g} = 1 \pm 1\%$$

from  $e^+e^- \rightarrow \tilde{v}\tilde{\nu} \quad \tilde{\nu} \rightarrow e^-\tilde{\chi}^+$

at this level of accuracy, radiative corrections become relevant

$$\frac{\delta g_{e\tilde{e}\tilde{b}}}{\sqrt{2}g'} = \frac{11g'^2}{48\pi^2} \log\left(\frac{m_{\tilde{q}}}{m_{\tilde{e}}}\right)$$

$$\frac{\delta g_{e\tilde{e}\tilde{b}}}{\sqrt{2}g} = \frac{3g'^2}{16\pi^2} \log\left(\frac{m_{\tilde{q}}}{m_{\tilde{e}}}\right)$$

the errors above correspond to a factor 3 in  $m_{\tilde{q}}$

$e^+e^- \rightarrow \tilde{\tau}^+\tilde{\tau}^-$  brings in two more features:

④ for large  $\mu, A_\tau$ ,  $\tilde{\tau}_L$  and  $\tilde{\tau}_R$  mix

$$m^2 = \begin{pmatrix} m_L^2 + m_e^2 + 0.27D & -m_\tau(A_\tau - \mu \tan\beta) \\ -m_\tau(A_\tau - \mu \tan\beta) & m_R^2 + m_e^2 + 0.23D \end{pmatrix}$$

$$D = -m_2^2 \cos 2\beta$$

this is relevant to large  $\tan\beta$  scenarios  
as a mechanism which gives light  $\tilde{\tau}, \tilde{b}, \tilde{t}$

to study mixing experimentally,

determine  $m(\tilde{\tau}_1)$  from energy dist of  $\tau$  decay products

then determine  $\theta_\tau$  from  $\sigma(e_L^-), \sigma(e_R^-)$

Nojiri Fujii Tsukamoto

100 fb<sup>-1</sup>

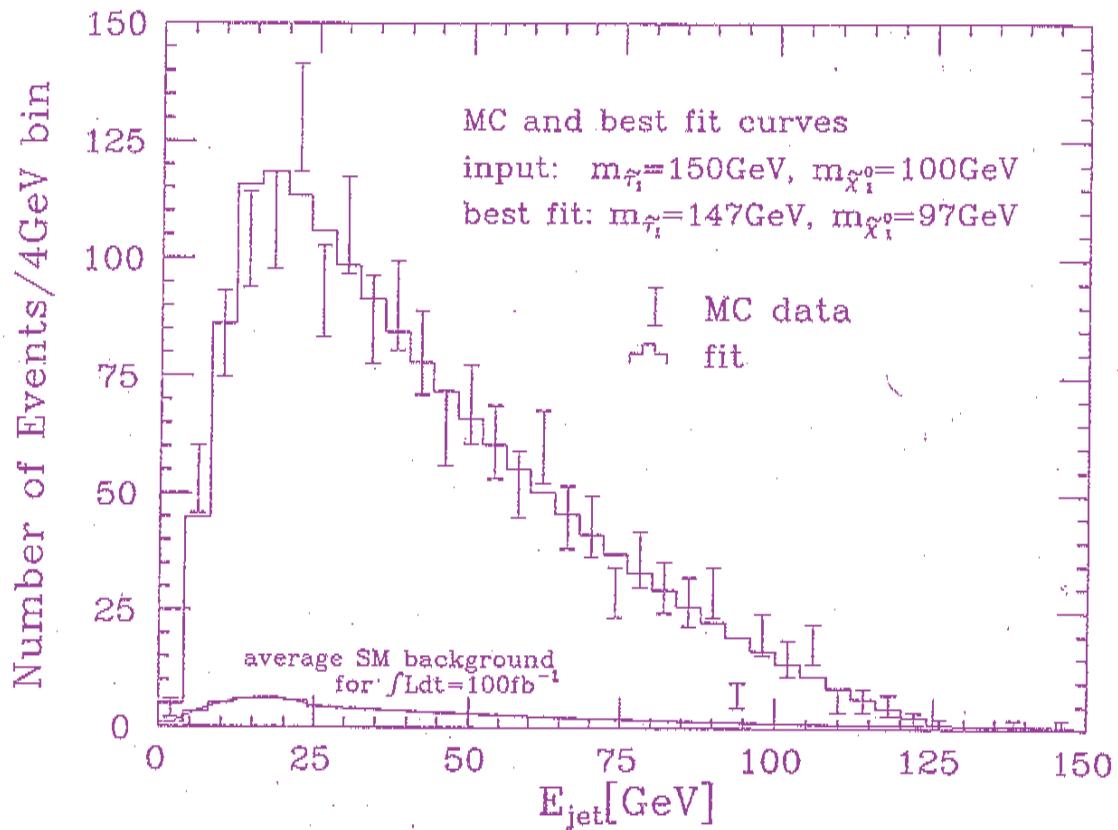
study:  $\tilde{\tau}_1^- \rightarrow \tau^- \chi_1^0$        $\tau^- \rightarrow \bar{\nu}\nu$

find:

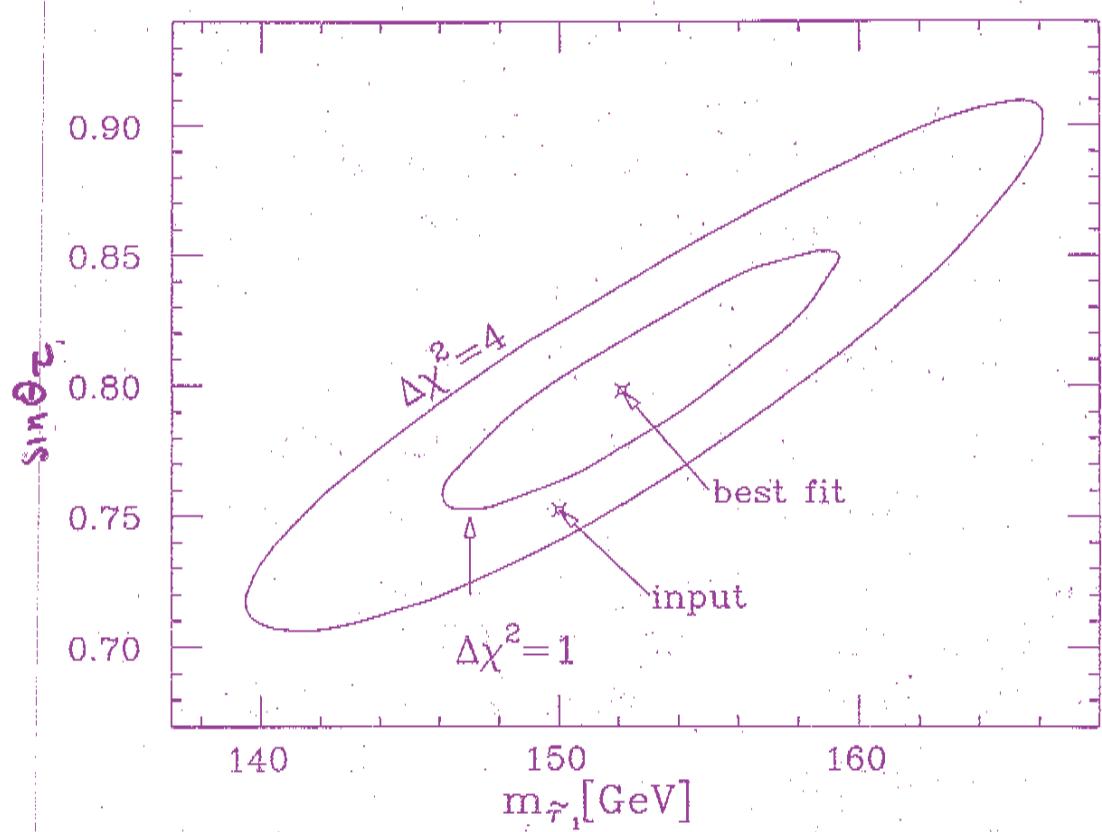
$$\frac{\Delta m_\tau}{m_\tau} = 1.5\% \quad \Delta(\sin \theta_\tau) = 0.03$$

(using  $m(\chi_1^0)$  from other sources)

### Mass Fit to $\rho$ Energy Distribution of $10^4 \tilde{\tau}_1$ Pairs



### $\tilde{\tau}_1$ Mass and Mixing Angle Fit



②  $\tilde{\tau}^-$  polarization

$$\tilde{\tau}_R^- \rightarrow \tau_R^- + \text{gaugino} \\ \tau_L^- + \text{Higgsino}$$

Nojiri, Fujii Tsukamoto found  $\Delta P_C \sim 7\%$

this information can be used for  $\tilde{\tau}$  or  $\tilde{\chi}$  mixing studies.

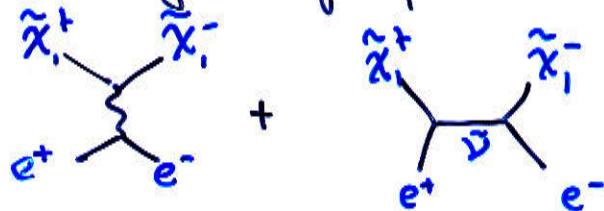
e.g. case of pure  $\tilde{\tau}_R^- \rightarrow \tau^- \chi_1^0$

$$1 - P_C = \frac{c_W^2}{4S_W} \cdot \frac{m_{\tilde{\tau}}^2}{m_W^2} \cdot \frac{1}{\alpha_s^2 \beta} \cdot \left| \frac{V_{31}}{V_{11}} \right|^2$$

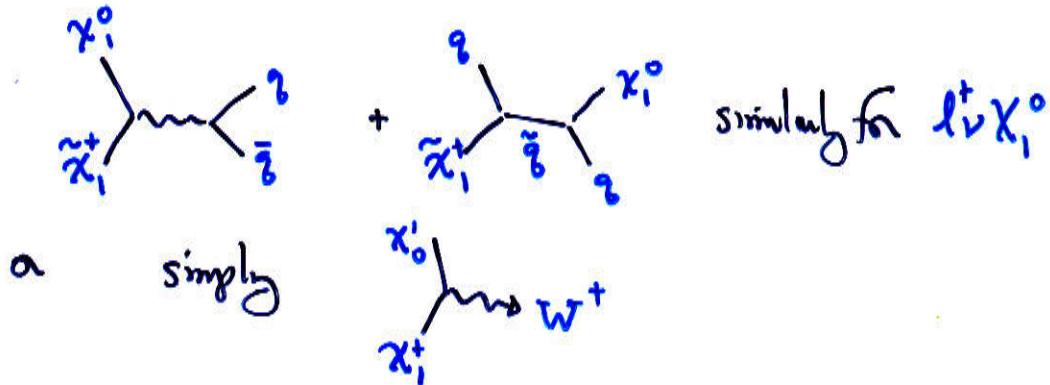
$$e^+ e^- \rightarrow \tilde{\chi}^+ \tilde{\chi}^-, \tilde{\chi}^0 \tilde{\chi}^0$$

Now switch to the case in which the  $\tilde{\chi}_1^+$  is the lightest charged superpartner

production:



decay:



a simply



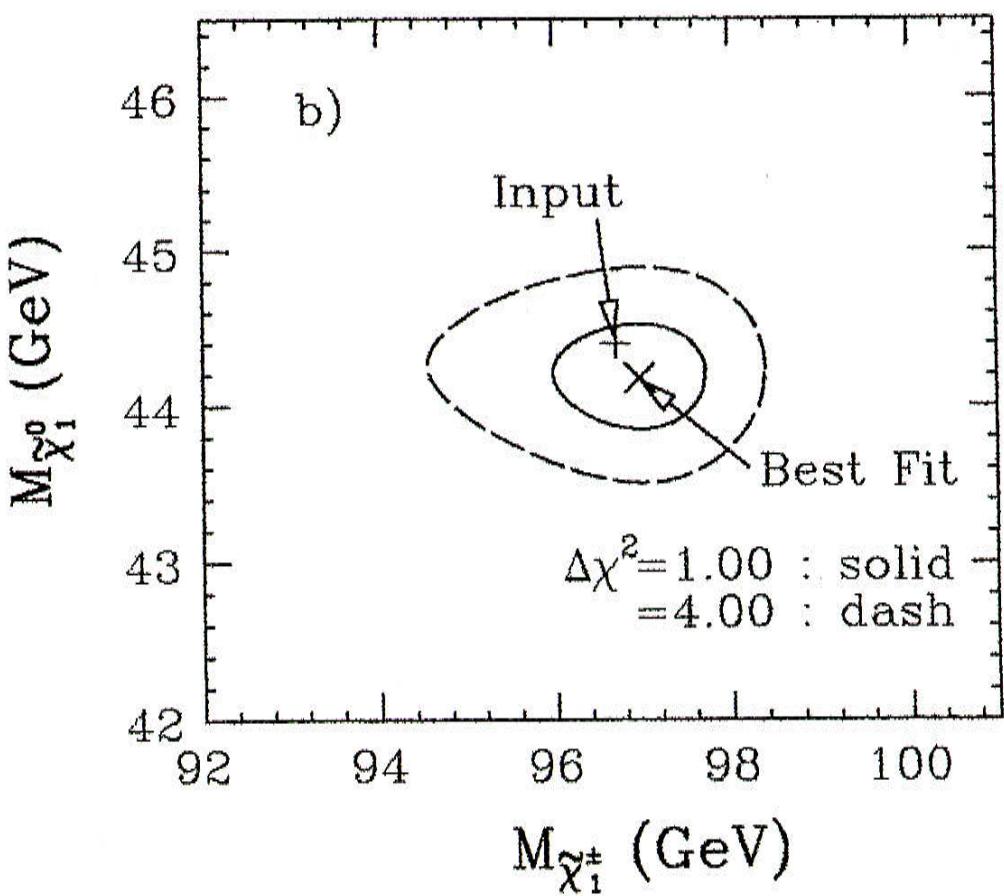
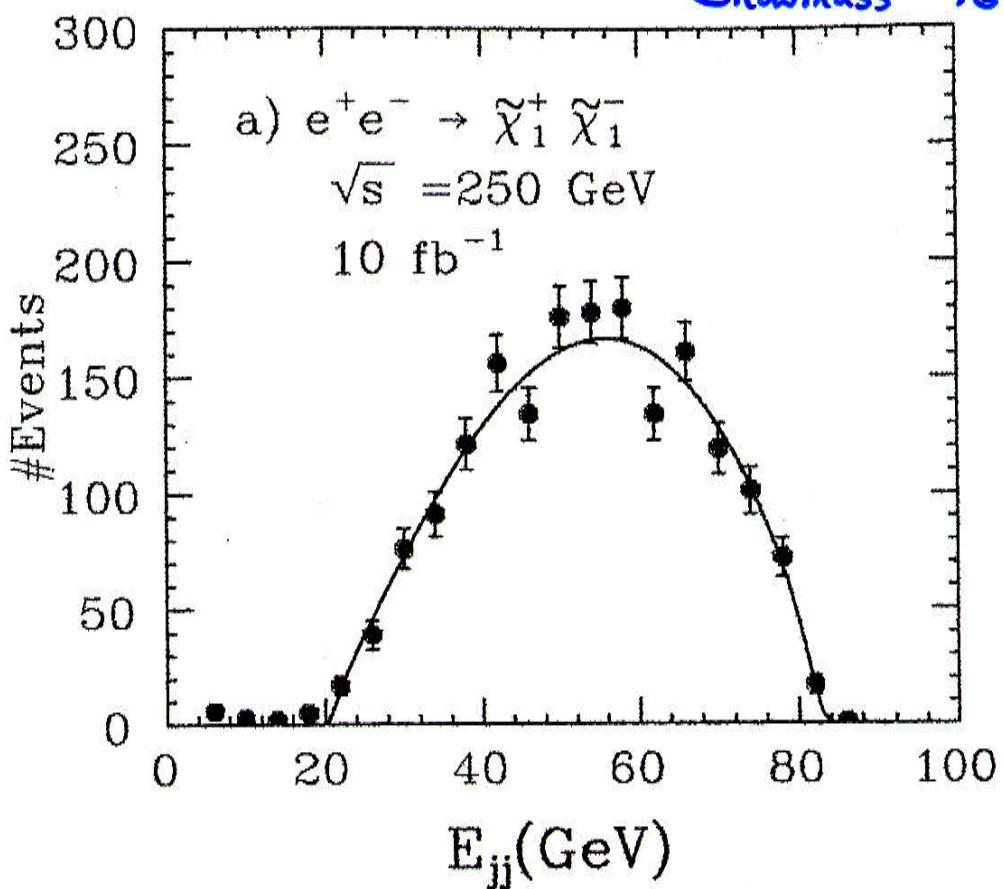
select events with

$$e^+ e^- \rightarrow \text{acoplanar } l + (q\bar{q})$$

$$(q\bar{q}) + (q\bar{q}) + \text{missing } E_T$$

for 2- or 3-body case, the endpoint technique gives masses to few-% accuracy

Shawmass '96



The masses of  $\tilde{\chi}_1^0 \tilde{\chi}_1^+ \tilde{\chi}_2^0 \dots$  give eigenvalues of the mass matrices. Can we also determine the mixing angles?

Consider  $e^- e^+ \rightarrow \tilde{\chi}_1^+, \tilde{\chi}_1^-$ :

- the  $\tilde{\omega}$  diagram decouples
- for  $E_{cm} \gg m_Z$ , the  $\gamma, Z$  diagrams form pure  $B^\pm$ , which couples only to  $\tilde{h}^\pm$
- for  $E_{cm} \gg m_{\tilde{\chi}}$ , the angular distribution becomes

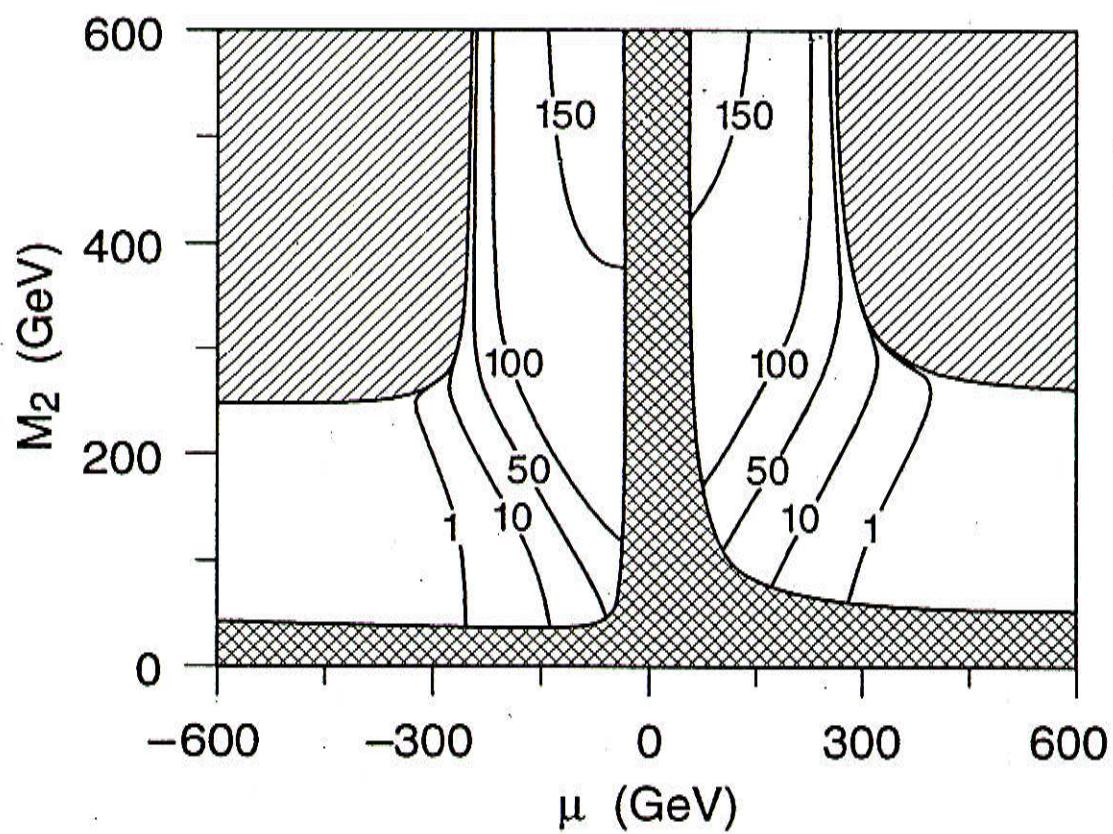
$$\frac{d\sigma}{d\cos\theta} \sim \sin^4\theta_+ (1+\cos\theta)^2 + \sin^4\theta_- (1-\cos\theta)^2$$

so

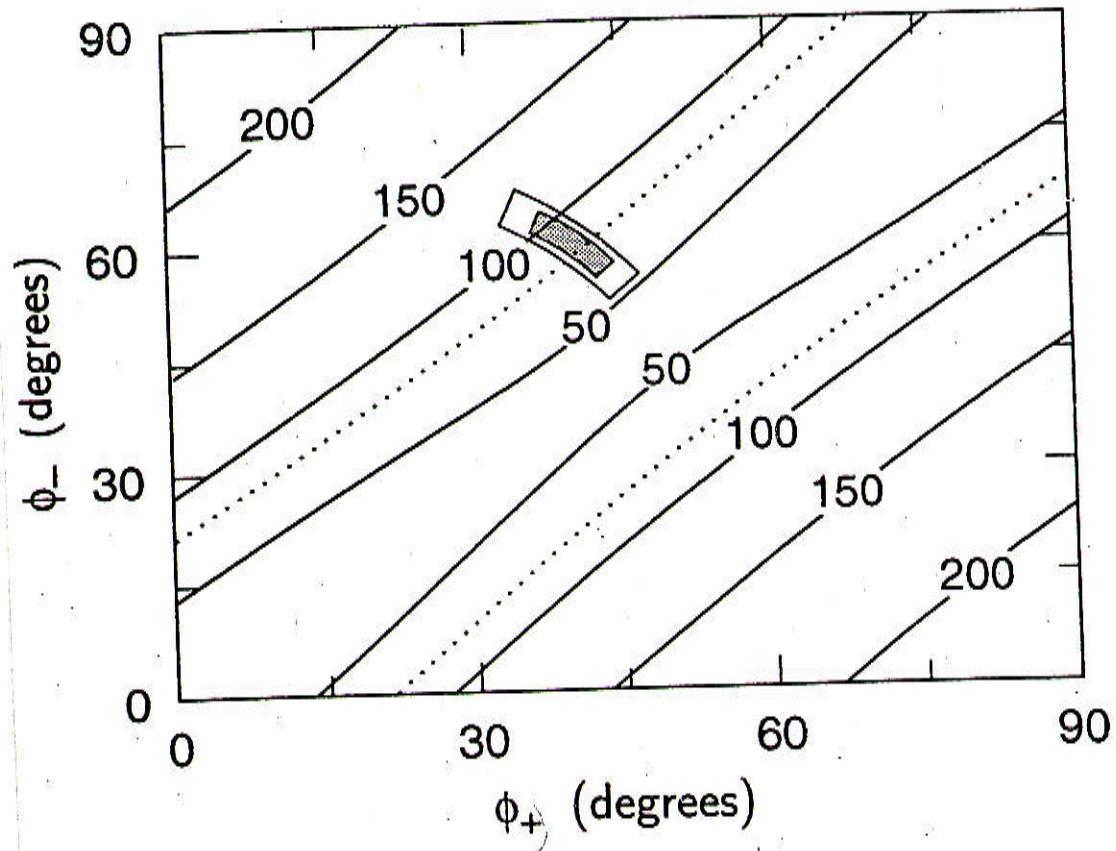
$\sigma(e^- p)$  gives the amount of  $\tilde{h}$  in the  $\tilde{\chi}_1^+$

$A_{FB}$  gives the relative mixing of  $(\tilde{\omega}^+, \tilde{h}^+)_L$  vs.  $(\tilde{\omega}^-, \tilde{h}^-)_L$

Feng et al.



Feng et al.



recall the form of the mass matrix

$$M_{\text{SB}} = \begin{pmatrix} m_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix}$$

The three parameters  $m(\tilde{\chi}_1^+)$   $\sigma(e_R^-)$   $A_{FB}(e_R^-)$   
can be exchanged for  $m_2$   $\mu$   $\tan\beta$

In the intermediate or mixed region,  $\tilde{\chi}_2^+$  is not so heavy  
measure it from the threshold for  $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_2^-$

at one such point studied by

J. Feng et al.

$$\frac{\Delta \mu}{\mu} = 1.5\% \quad 100 \text{ fb}^{-1}$$

$$\frac{\Delta m_2}{m_2} = 1.5\%$$

$$\Delta(\tan\beta) = 0.1$$

assuming SUSY. Relaxing this constraint,  
we have another test of SUSY relations

$$m_W = 80 \pm 23 \text{ GeV}$$

switching  $e^-$  polarization,

$\sigma(e^-_L e^+ \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-)$  shows strong destructive interference between the  $\gamma Z$  and  $\tilde{g}$  graphs. This is sensitive to  $m(\tilde{g})$  up to about  $m(\tilde{g}) \sim 2\sqrt{s}$

finally, we can measure  $BR(\tilde{\chi}_1^+ \rightarrow l^+ \nu \chi_1^0)$

in the Higgsino region

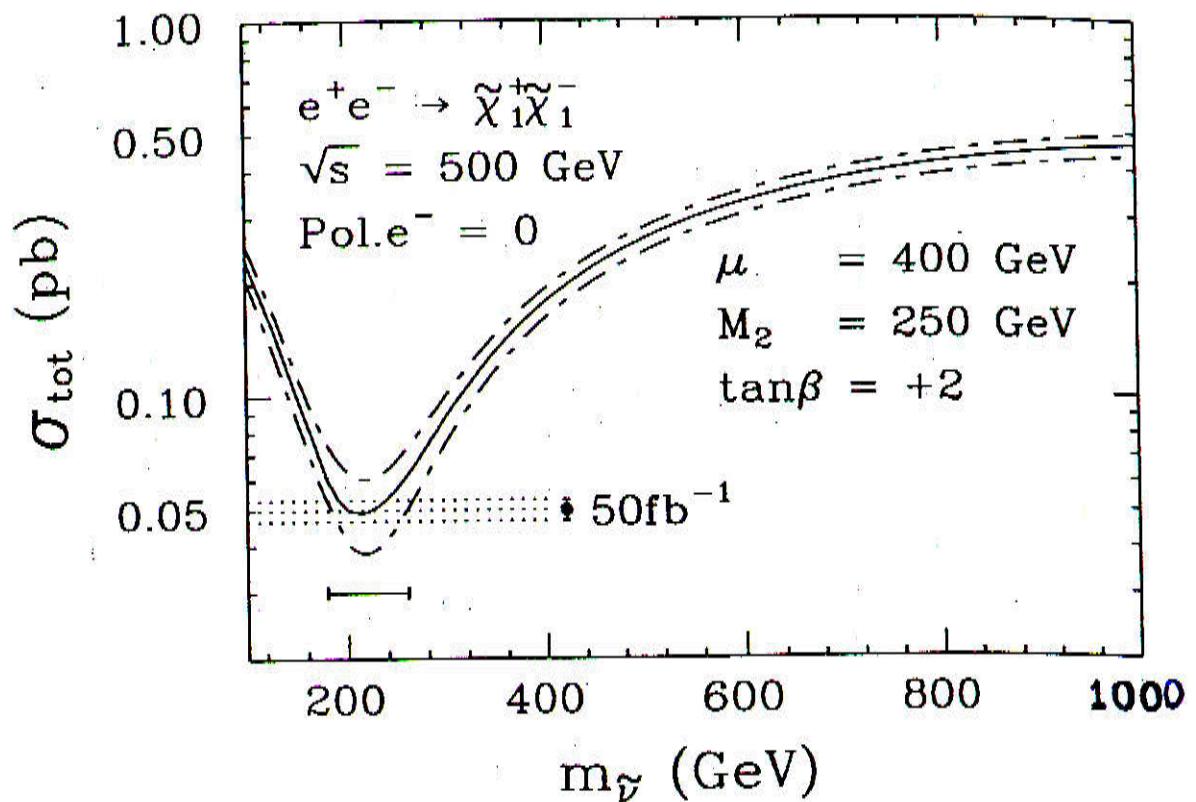
$$BR(\tilde{\chi}_1^+ \rightarrow l^+) \approx BR(W^+ \rightarrow l^+ \nu)$$

in the gaugino region, diagrams w.

$\tilde{l}$  exchange enhance this  $BR$

the effect is stronger at large  $\tan\beta$ .

Tsukamoto et al.



$\text{BR}(\tilde{\chi}_1^+ \rightarrow l\nu \tilde{\chi}_1^0)$

Frey and Strassler

$$\tan\beta = 2$$

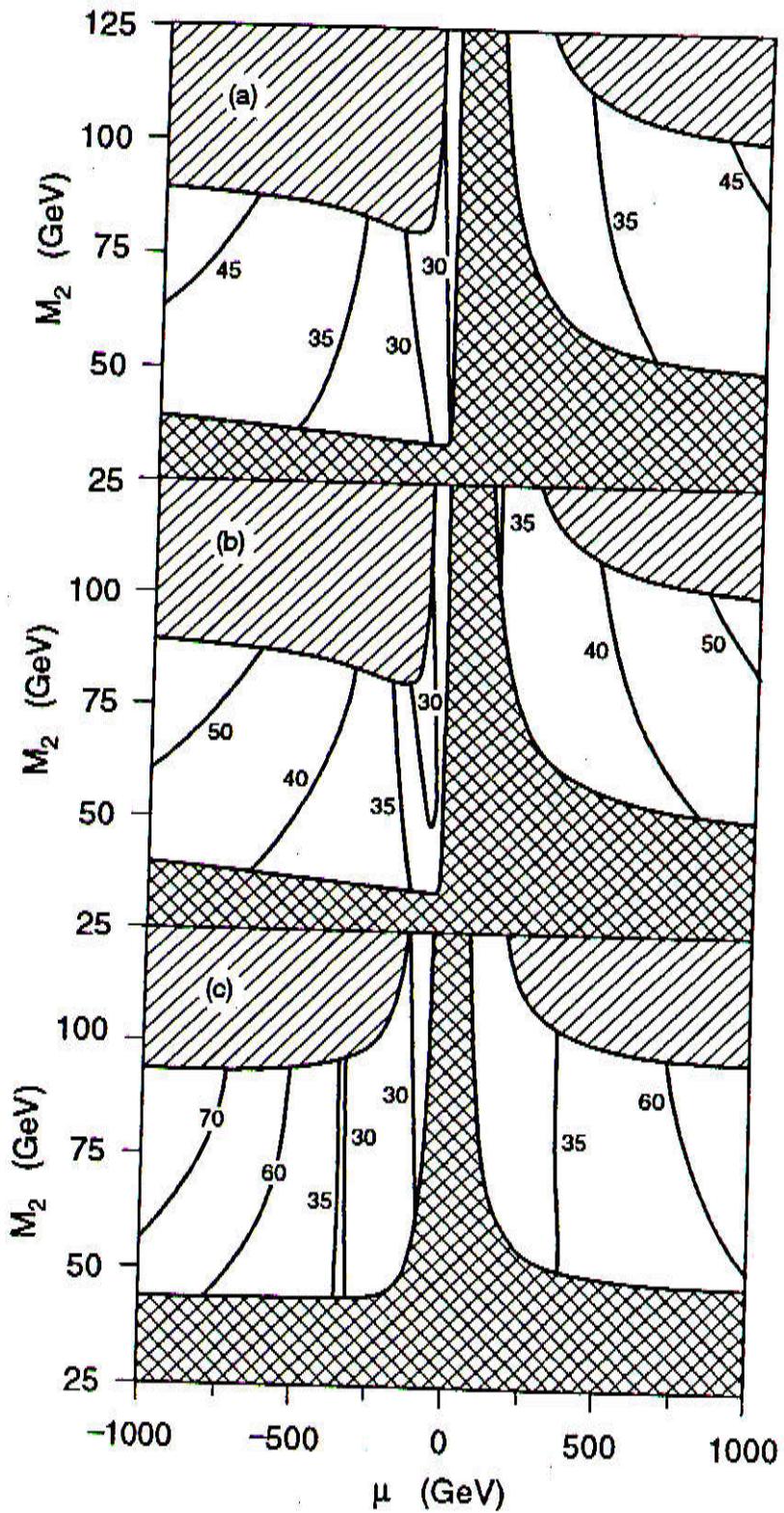
$$m_{\tilde{e}}, m_{\tilde{q}} = 200, 200$$

$$\tan\beta = 2$$

$$m_{\tilde{e}}, m_{\tilde{q}} = 200, 800$$

$$\tan\beta = 10$$

$$m_{\tilde{e}}, m_{\tilde{q}} = 200, 200$$



$$e^+ e^- \rightarrow \tilde{t} \tilde{t}, \tilde{b} \tilde{b}$$

$\tilde{t}$   $\tilde{b}$  may be driven to lower mass than the other squarks by

- renormalization group evolution associated with electroweak symmetry breaking
- large L-R mixing

The analysis of  $m, \Theta$  is similar to that for  $\tilde{\chi}$

Analyses in the literature:

for a point with  $m(\tilde{t}) < m(t)$ ,  $\tilde{t}_i \rightarrow b \tilde{\chi}_i^+$

Snowmass '96:

the endpoint technique w. known  $m(\tilde{\chi}_i^+)$

$$\text{since } m(\tilde{t}_i) = 180 \pm 6 \text{ GeV}$$

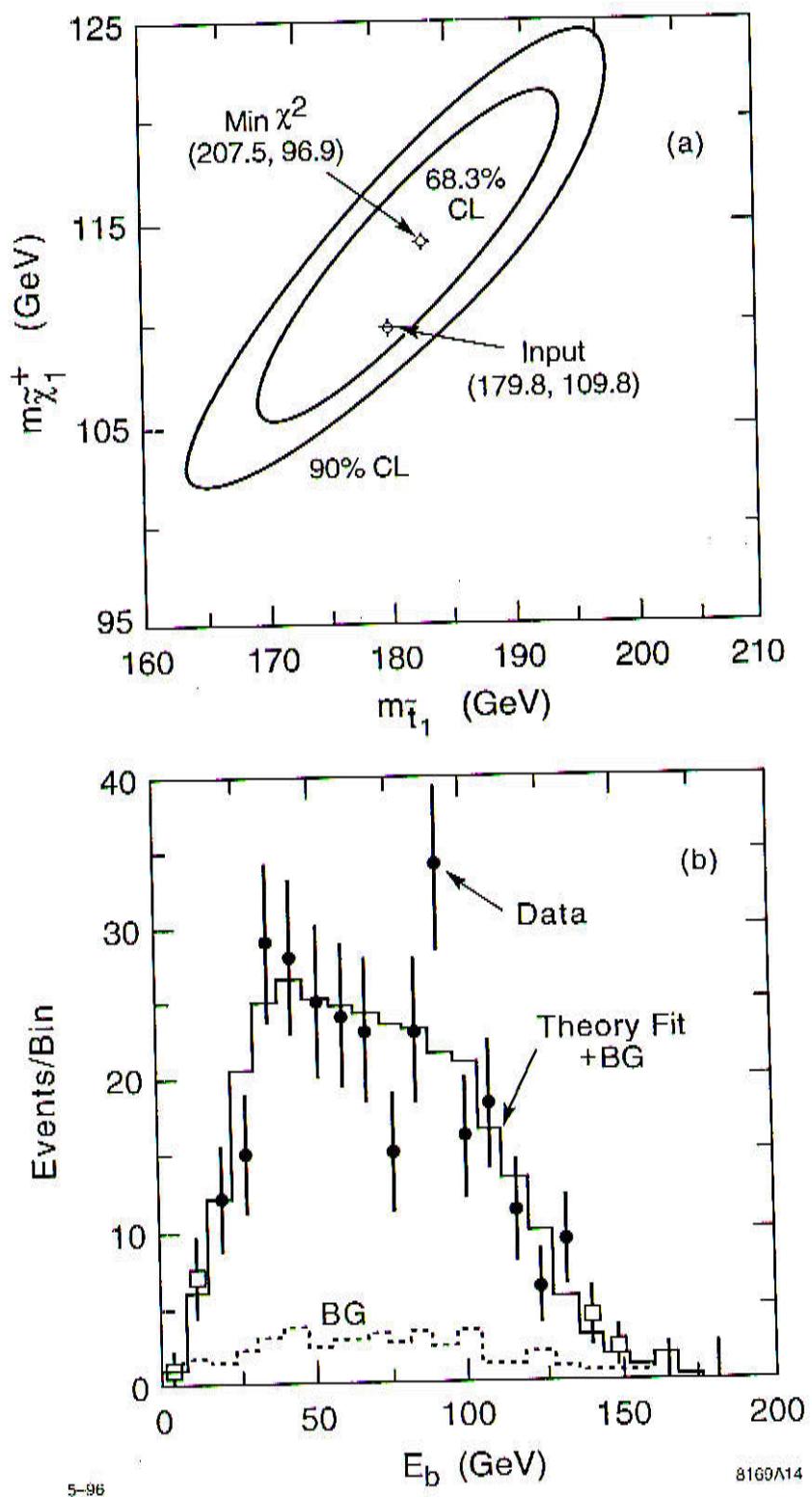
Baerl et al:  $\sigma(e_L^+), \sigma(e_R^-)$  give

$$m(\tilde{t}) = 180 \pm 7 \text{ GeV}$$

$$\cos \Theta_t = 0.57 \pm .06$$

Snowmass '96

50 fb<sup>-1</sup>



by way of review ,

What measurements does the LC add to the  
ATLAS analyses at the LHCC SUGRA points ?

notes on the following table :

- "X" denotes  $m(X)$
- all LHC pts have  $h^0$ ,  $\min(\tilde{g}, \tilde{g})$   
typically  $\tilde{q} g \rightarrow q \chi^0$  can be used to estimate  
 $m(\tilde{q} g)$ ; I call this "  $\tilde{q}$  from PD "
- LHC "measures"  $\tan\beta$  using the theory of  $m(h^0)$   
too complex for me !
- all LHC pts are in the gaugino limit;  
LC can demonstrate this, but in this limit  
 $\chi_i^+$  does not give  $\mu$
- LC adds tests of model-independent SUSY  
relations for the particles listed
- for LC, "  $E_{cm}$  needed" = threshold + 50 GeV

<u>Point</u>	<u>LHC</u>	<u>LC</u>	<u><math>E_{cm}</math> needed</u>
1,2	$\tilde{g}$ from $m(hq)$	$\tilde{\chi}_1^0 \tilde{\chi}_1^+ \tilde{\chi}_2^0 \tilde{\nu}$	700.
	$\tilde{g} \tilde{g}$ from PD	$\tilde{l}_R \tilde{l}_L$	1030.
3 (light susy)	$(\tilde{\chi}_2^0 - \tilde{\chi}_1^0), (\tilde{b} - \tilde{\chi}_1^0), (\tilde{g} - \tilde{b})$ $\tilde{g}$ from PD	$\tilde{\chi}_1^0 \tilde{\chi}_1^+ \tilde{\chi}_2^0 \tilde{\nu}$ $\tilde{l}_R \tilde{l}_L$ all $\tilde{q}$ , $\tilde{b} \bar{b}$ $\tilde{g}_L - \tilde{g}_R$ $H^0 A^0 H^\pm$	250 450 700 810
4 (large $m_0$ )	$(\tilde{\chi}_2^0 - \tilde{\chi}_1^0), (\tilde{g} - \tilde{\chi}_1^0)$ $\tilde{\chi}_2^0 \tilde{g}$ from PD	$\tilde{\chi}_1^0 \tilde{\chi}_1^+ \tilde{\chi}_2^0 \tilde{\nu}$ $\tilde{\chi}_2^+ \tilde{\chi}_3^0 \tilde{\chi}_4^0 \rightarrow \mu, \tan \beta$	350 680
5 (light sleptons)	$\tilde{\chi}_1^0 \tilde{l} \tilde{\chi}_2^0 \tilde{q}_L$ from long decay chain	$\tilde{l}_R$ $\tilde{\chi}_1^0 \tilde{\chi}_1^+ \tilde{\chi}_2^0 \tilde{l}_L \tilde{\nu}$ $\tilde{\chi}_2^+ \tilde{\chi}_3^0 \tilde{\chi}_4^0 \rightarrow \mu \tan \beta$	360 510 1050
6 (large $\tan \beta$ )	$(\tilde{\chi}_2^0 - \tilde{\chi}_1^0), (\tilde{b} - \tilde{\chi}_1^0), (\tilde{g} - \tilde{b})$ $\tilde{q}$ from PD	$\tilde{\chi}_1^0 \tilde{\chi}_2^+ \tilde{\chi}_2^0 \tilde{\nu} H^0 A^0$ $\tilde{l}_R \tilde{b} \tilde{c} \Theta_c$ $\tilde{b} \tilde{l}_L \Theta_L$ $\tilde{b} \Theta_b$	360 490 530 780 840

footnote: Why did  $\tilde{\chi}_i^+$  appear at LC  
in all scenarios?

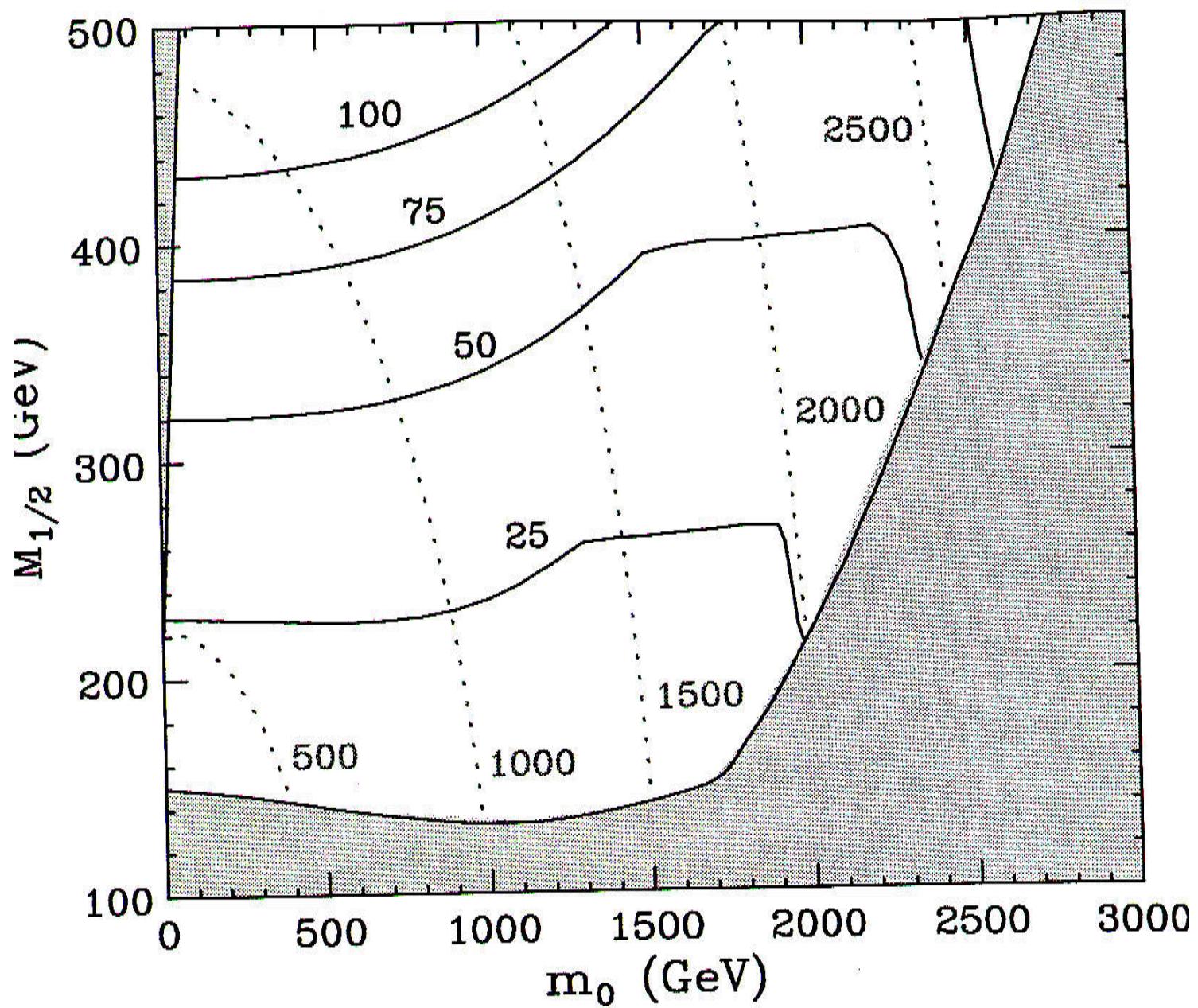
In the class of models studied here  
electroweak symmetry-breaking appears at  
100 GeV without excessive fine-tuning  
only if

$$1 \text{ TeV} \gtrsim \mu, m(\tilde{g}) = 3.5 m(\tilde{\chi}_i^+)$$

The squark and slepton masses do not have a  
similar strong constraint.

Other models of the superspectrum  
(e.g. "gauge mediation")  
require  $m(\tilde{t}) \sim m(\tilde{\chi}^+)$

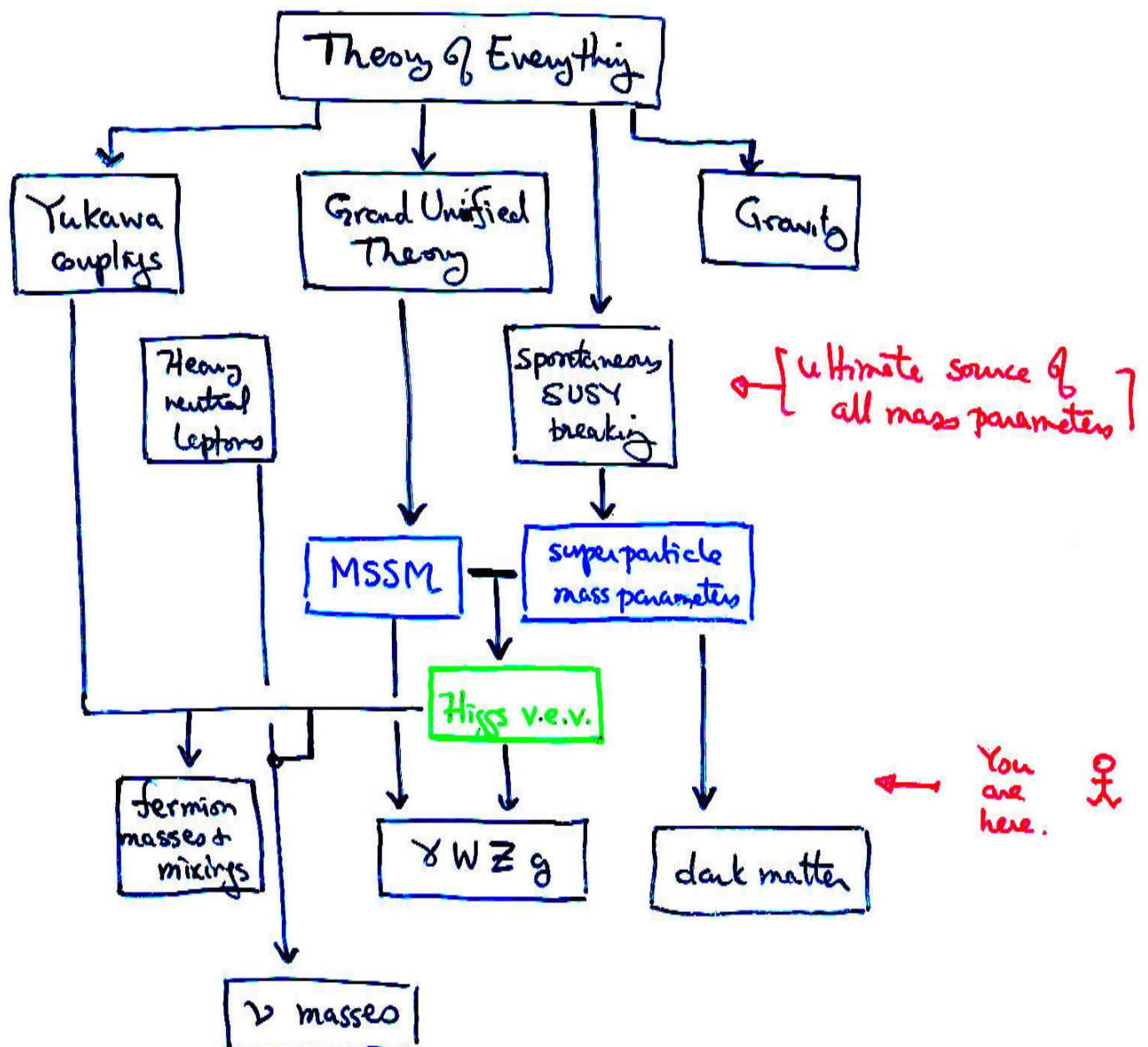
Feng, Matchev, Moroi



this brings us to consideration of  
theories of the SUSY spectrum

What questions do these theories raise,  
and how do we answer them ?

## Structure of a typical SUSY model :



What is the origin of spontaneous SUSY breaking?

We don't have a clue!

There are two important constraints

- ① SSSB at tree level in the Standard Model sector  
implies  $\tilde{g}$  or  $\tilde{q}$  below  $m_Z$ .

In typical models, SUSY violating terms are  
effective soft operators generated at a higher scale

- ② The absence of flavor-changing effects from SUSY  
(e.g. in  $K_L^0 - K_S^0$ ,  $\mu \rightarrow e\gamma$ )  
implies that these mass terms are approximately  
flavor-diagonal

e.g. 
$$\frac{(\Delta m_{RR}^2)_{sd}}{m_d^2} < 10^{-2} \left( \frac{m_d}{300 \text{ GeV}} \right)^2$$
 Gabbiani Masiero

- strategies for models:
- "universality"
  - "alignment"
  - heavy scalars

## explicit models for the generation of soft SUSY-breaking terms

### "Gravity mediation"

gauginos masses come from

direct  $\mathcal{O}(\frac{1}{m_{pl}})$  coupling to YM Lagrangian

scalar masses come from direct  $\mathcal{O}(\frac{1}{m_{pl}^2})$  coupling of superpotentials

universality is not required; may be added as an assumption  
 $m(\tilde{q}) \sim \text{TeV}$

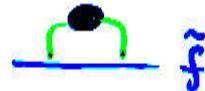
### "Gauge mediation"

SSSB sector couples to SM gauge interactions

gauginos masses come from



scalar(mass)<sup>2</sup>'s come from



universality arises naturally

$$m(\tilde{q}) \sim \left( \frac{\sqrt{F}}{100 \text{ TeV}} \right)^2 \text{ eV}$$

sometimes called "SUGRA", or  
"the Monte Carlo generator described in [93]"

## "Anomaly mediation"

no direct tree-level coupling in supergravity

breaking of scale invariance by loop corrections  
generates  $\mathcal{O}(M_{\text{GUT}})$  masses

universality arises naturally

$$m(\tilde{g}) \sim 100 \text{ TeV}$$

mixtures of these scenarios can arise

In particular,

gauge mediation w. a multiplet w.  $M \rightarrow M_{\text{GUT}}$

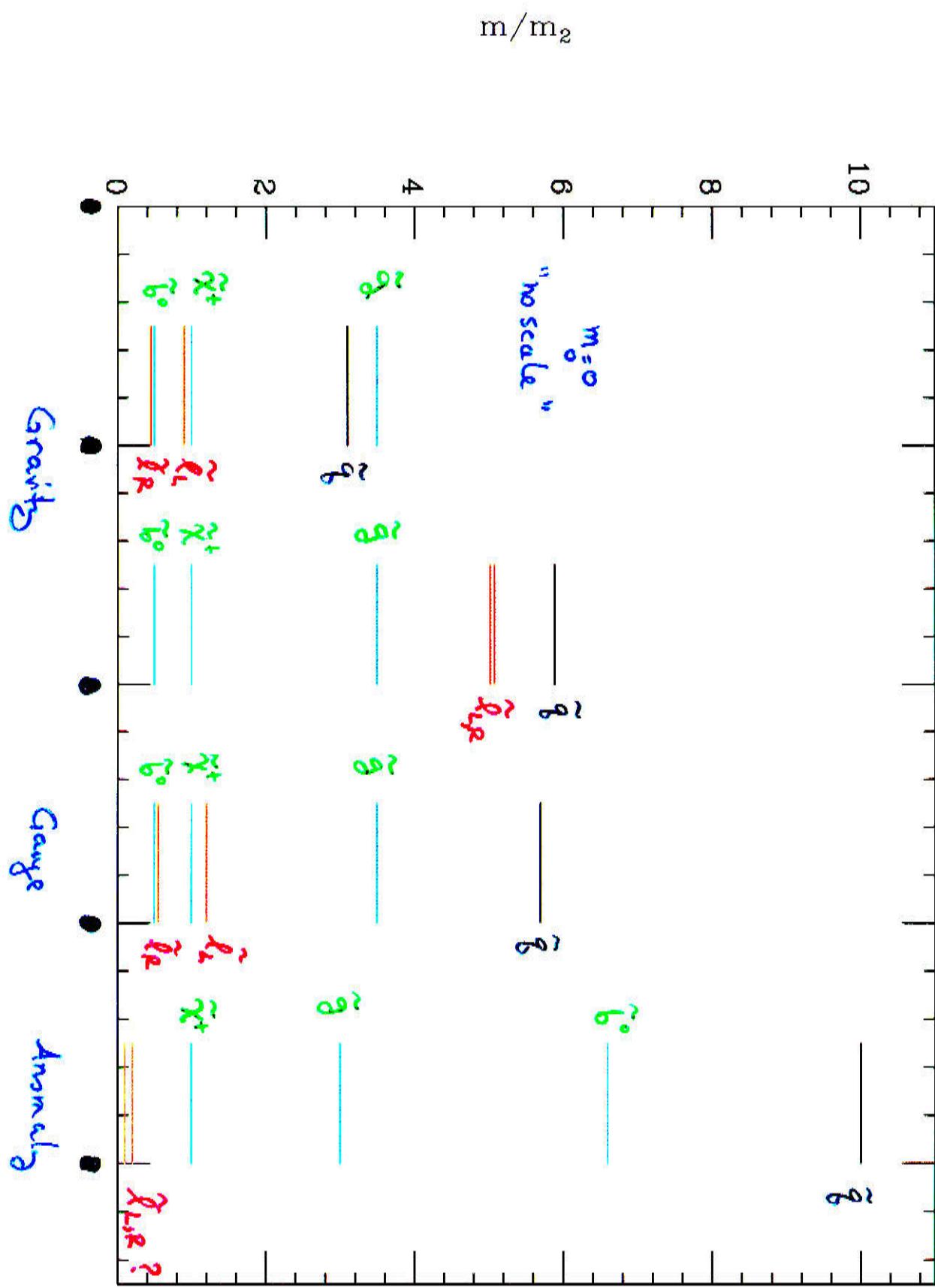
approaches gravity mediation w.

$$\text{universal } m_0 \sim m_{1/2}$$

## (Very much simplified) mass relations

notation :  $\beta_i = -\frac{b_i}{(4\pi)^2} g_i^2$        $\gamma_f = -\frac{a_i}{(4\pi)^2} g_i^2$

	<u>Gaugino m<sup>2</sup></u>	<u>Scalar m<sup>2</sup></u>
<u>Gravity</u>	$(\frac{\alpha_i}{\alpha_2})^2 m_2^2$	$m_0^2 + \sum_i 2C_i \frac{\alpha_i^2 - \alpha_{i0}^2}{b_i d_2} m_2^2$
<u>Gauge</u>	$(\frac{\alpha_i}{\alpha_2})^2 m_2^2$	$\sum_i 2C_i \frac{\alpha_i^2}{\alpha_2^2} m_2^2$
<u>Anomaly</u> mediation	$(\frac{b_i}{b_2})^2 m_2^2$ $\tilde{\omega}^+ \tilde{\omega}^0$ are lightest gauginos.	$\sum_i 2a_i \frac{b_i \alpha_i^2}{\alpha_2^2} m_2^2$ prediction for $\tilde{l}_L \tilde{l}_R$ (mass) <sup>2</sup> is negative



## Distinctive signatures of gauge, anomaly mediation

### Gauge mediation:

the lightest neutralino or slepton may decay by

$$\tilde{\chi}_1^0 \rightarrow \gamma \tilde{g}$$

$$\tilde{l}^- \rightarrow l \tilde{e} \quad \text{or} \quad \tilde{t}^- \rightarrow t \tilde{c}^+ \tilde{c}^-, \tilde{c}^- \rightarrow c \tilde{q}$$

with  $c\tau \sim \left(\frac{1000 \text{ TeV}}{\sqrt{F}}\right)^4 \text{ cm}$  for  $m \approx 200 \text{ GeV}$

note that  $\sqrt{F}$  may range from  $10 \text{ TeV}$  to  $10^9 \text{ TeV}$

### Anomaly mediation

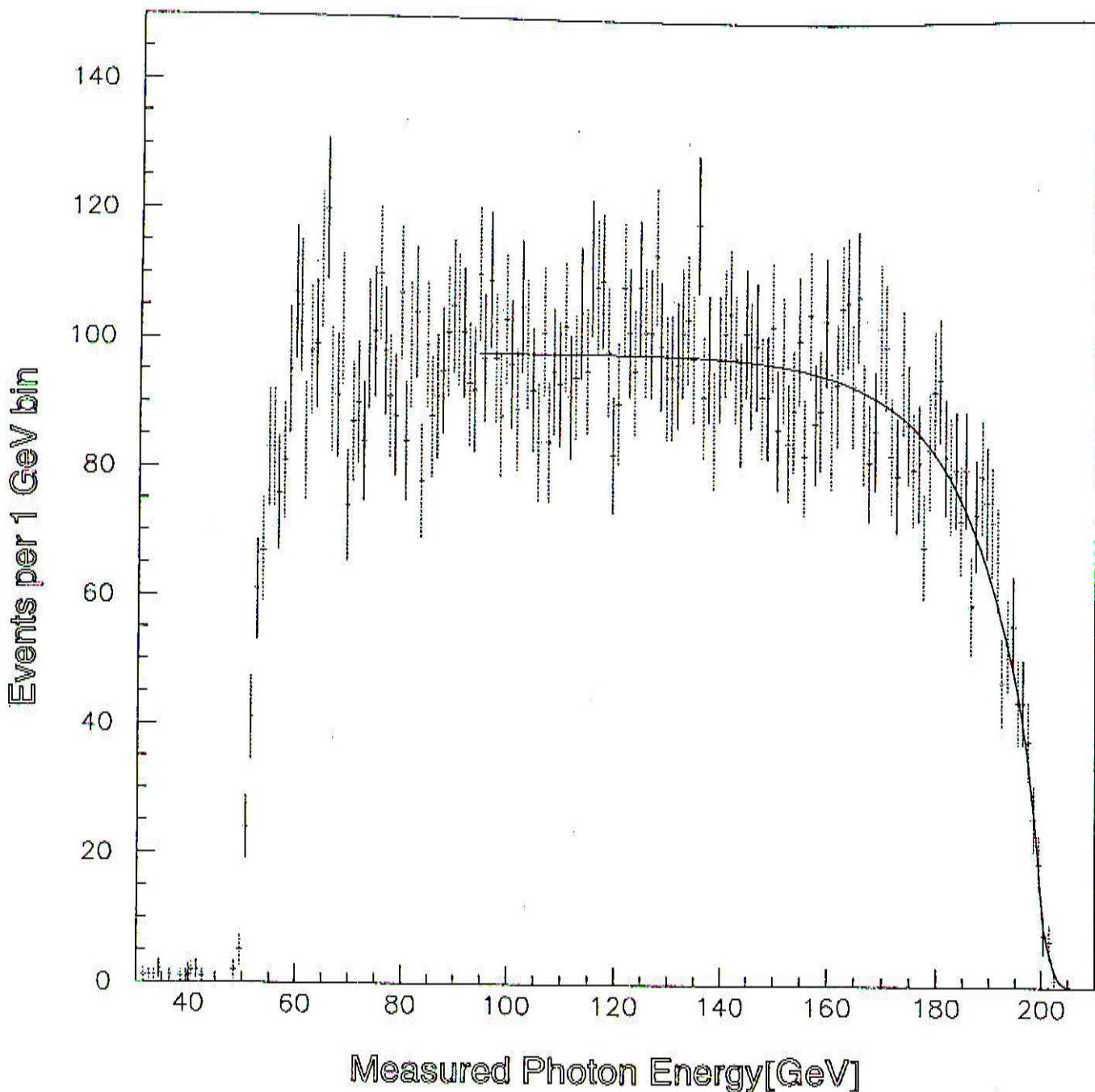
the lightest superparticles are  $\tilde{\omega}^+ \tilde{\omega}^0$

with  $\Delta m < 500 \text{ MeV}$   $\tilde{\omega}^+ \rightarrow \tilde{\omega}^0 \pi^+$

$\tilde{\omega}^+$  is a "stable particle" with  $c\tau \gtrsim 10 \text{ cm}$

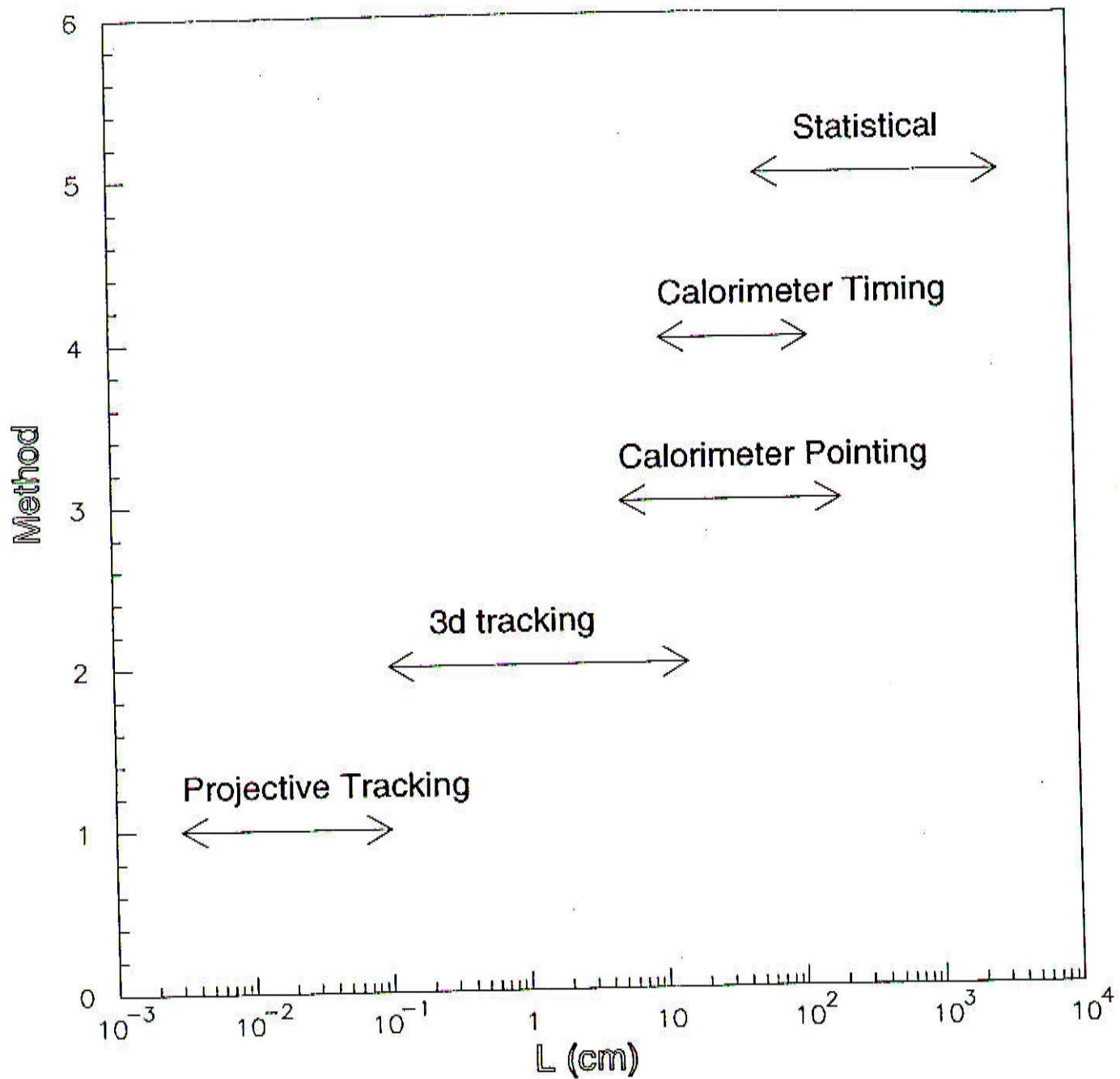
Ambrosanio + Blair

*Model 2 - Photon Energy Spectrum*



Ambrosanio + Blair

### Summary of Techniques



## Electroweak symmetry breaking

occurs naturally as a consequence of  
SUSY + large top Yukawa coupling

since RG evolution of  $m^2(\phi_2)$  drives  
this parameter negative

the same negative terms affect  $\tilde{t}$ ,  
perhaps also  $\tilde{b}, \tilde{c}$

so need to:

measure  $\mu, \tan\beta$

$\tilde{t} \tilde{b} \tilde{c}$  mix. parameters

caution: RG evolution of  $A_t$  has an infrared attractor;  
 $t$  is very difficult to run  $A_t$  or  $m^2(\phi_2)$   
back to the GUT scale.

by way of review,

## Survey the full program of SUSY measurements

- Is it really SUSY ?
  - quantum nos. , fermion or boson ?
  - identification of complete sets of partners
  - SUSY relation of couplings
- Major spectrum parameters
  - gauginos / Higgsinos mixing
  - gaugino mass ratios :  $m_1 : m_2 : m_3$
  - flavor universality of  $\tilde{q}_L, \tilde{l}_L, \tilde{l}_R$  masses
  - $\tilde{q} : \tilde{l}_R : \tilde{l}_L$  mass ratios
  - special signatures of gauge or anomaly mediation
- Third generation and electroweak symmetry breaking
  - $\mu, \tan\beta$
  - $\Delta m, \Theta$  for  $\tilde{t}, \tilde{b}, \tilde{\tau}$
  - $h^0$  mass and BR's
  - $H^0 A^0 H^\pm$
- Finer details
  - $\tilde{q}_L - \tilde{q}_R, \tilde{u}_R - \tilde{d}_R$
  - radiative corrections to coupling relations
  - slepton flavor mixing
  - phases, CP violation

snapshots of additional points

### CP violation

simple formulae for  $d\sigma/d\cos\Theta$  w. polarized beams  
make this a place to hunt for phases

### Lepton flavor violation

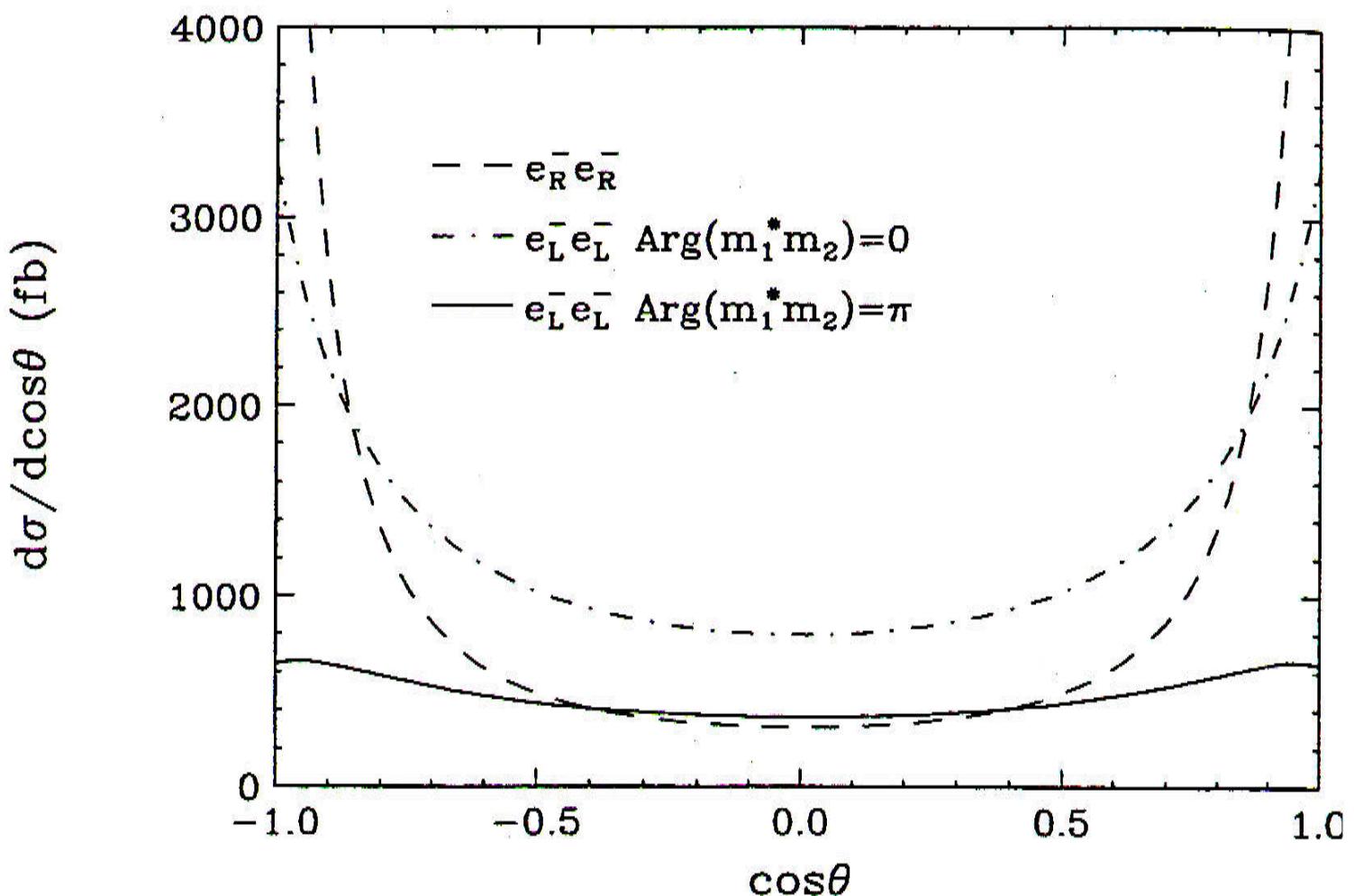
can occur through slepton mixing;  
the most sensitive tests use  $e^-e^- \rightarrow e^-\mu^-$

### R-parity violation

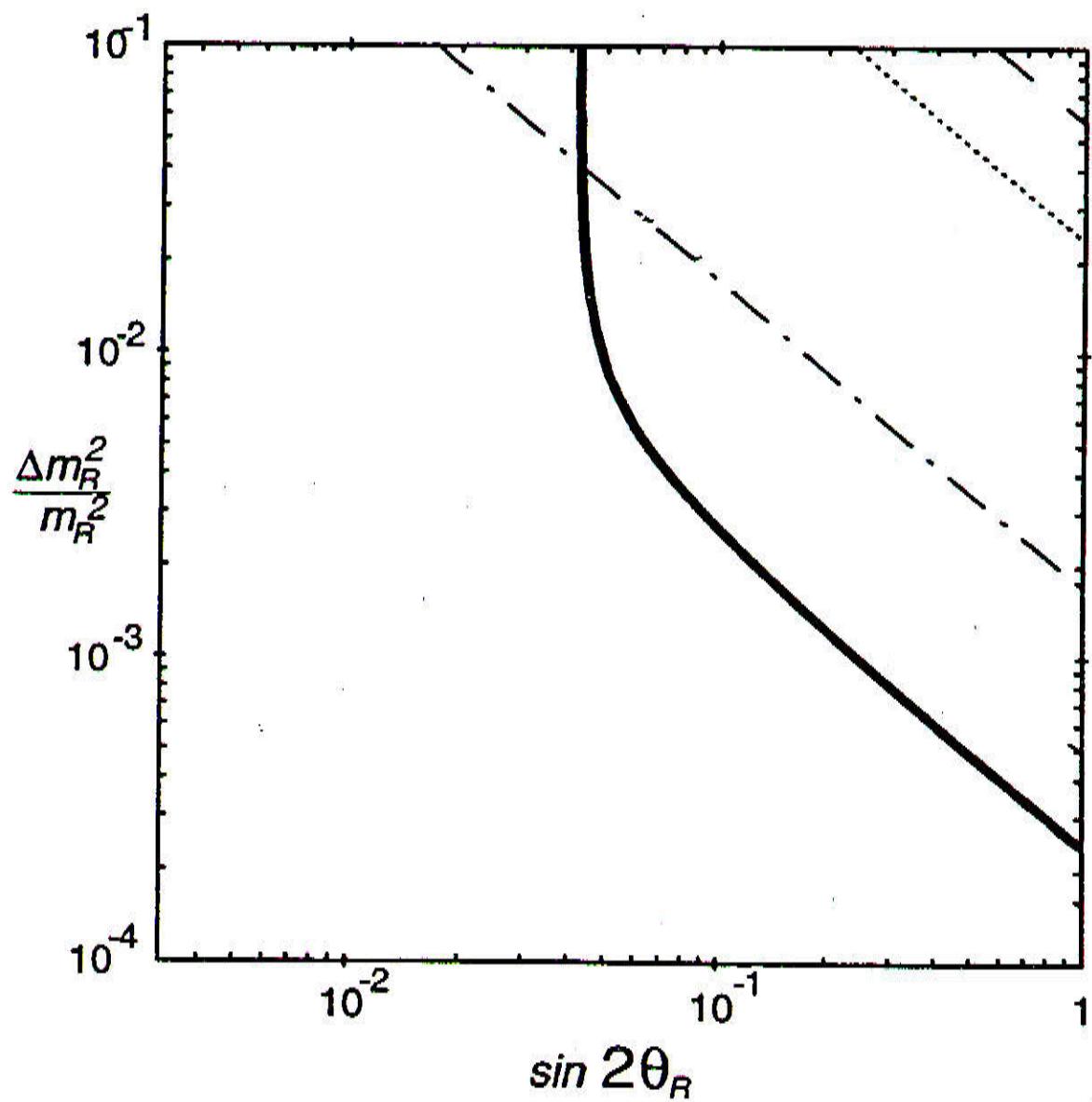
the basic set of production measurements is the same;  
only the selection cuts are different

$\tilde{\gamma}_i$  appears as a resonance;  
sensitivity to  $\Delta_{eei} \sim 0.01$

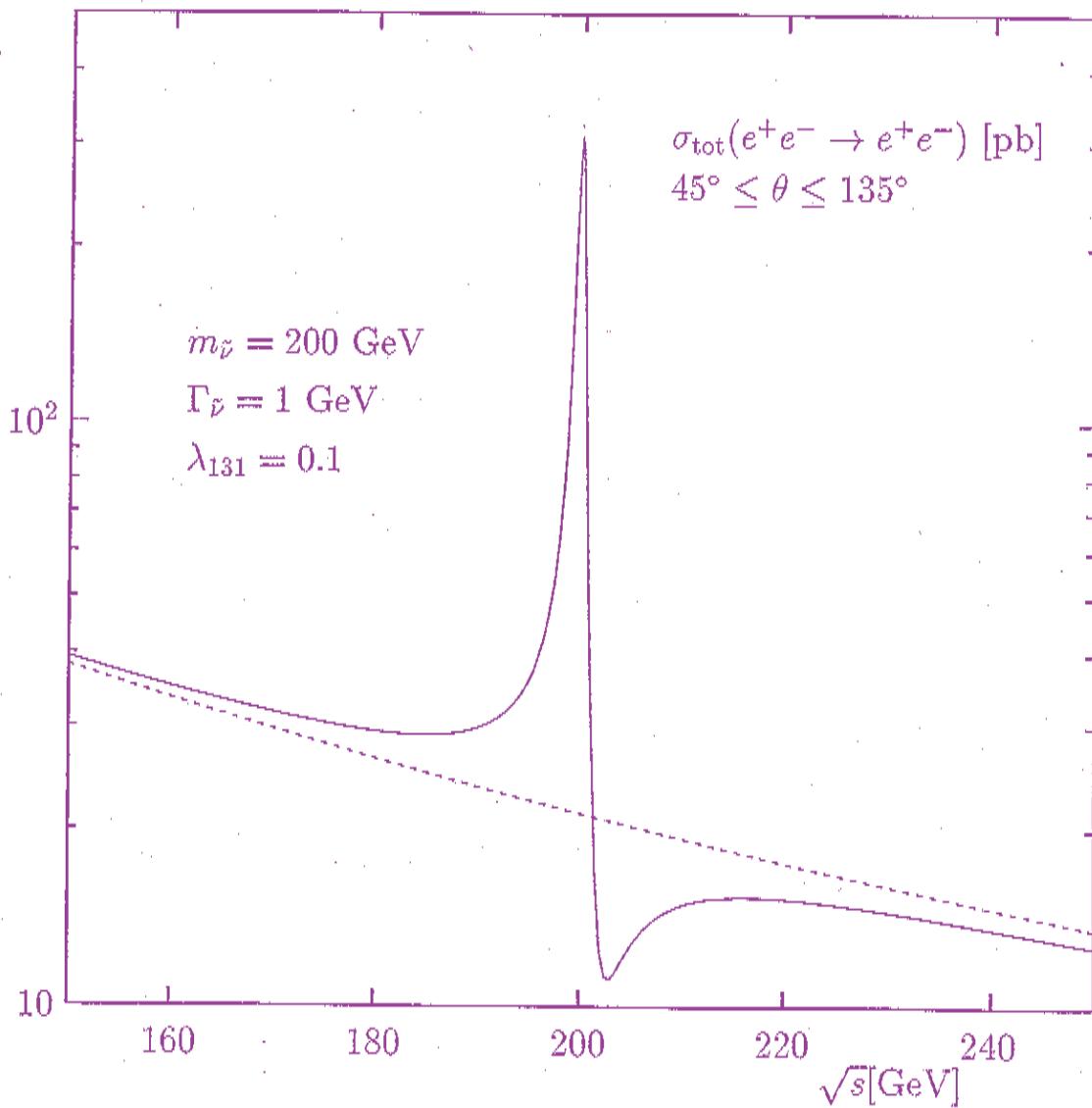
Thomas



Feng



Kalinowsky et al.



## Extra dimensions

superstring theory predicts extra space dimensions,  
we should be trying to find them

they could occur with any small size

Arkani-Hamed,  
Dimopoulos, Dvali

1 mm - 1 fm

"maxi"

Antoniadis

$1/\text{TeV}$

"midi"

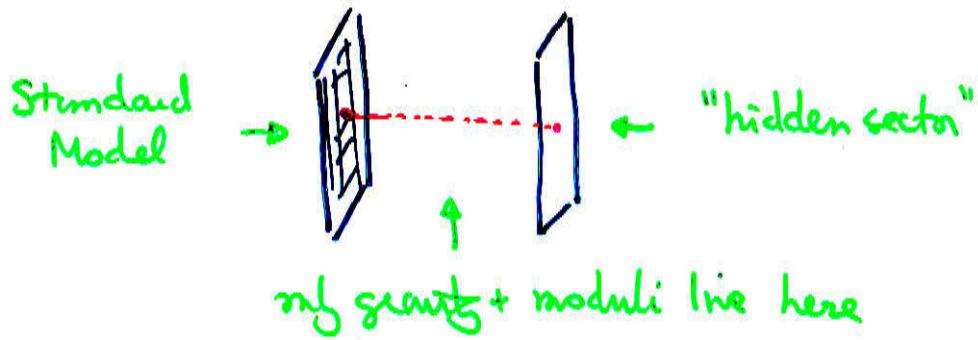
Hořava - Witten

$1/m_{\text{GUT}}$

"mini"

The first two cases have distinctive  
phenomenology at TeV colliders.

- In the third case, we must rely on the picture of SUSY breaking



Is there an "out of this world" SUSY spectrum that can be predicted precisely?

Horava : Gravity mediation w.  $m_0 = 0$  !  
Randall + Sundrum : Anomaly mediation !

Theorists need to resolve this;  
experimenters should be aware of the potential.

Conclusion :

The discovery of supersymmetry would open  
a new world and a rich experimental program

There is plenty of glory available here  
for both  $p\bar{p}$  and  $e^+e^-$  experiments